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Analysis of Simulated Drift Patterns of a High Altitude Balloon Surveillance System

by

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This study evaluates the potential of high altitude balloons as surveillance platforms. It begins with the mobile Theater Ballistic Missile (TBM) detection problem encountered during the Persian Gulf War of 1990-1991 and it describes a possible scenario using high altitude balloon surveillance systems to locate TBM's accurately enough for effective engagement by strike assets. It presents the history and military use of balloons, and it describes the current state of technology of differing balloon types. Atmospheric circulation impacting balloon drift is presented along with a description of available atmospheric models. Trajectory prediction programs are reviewed and a revised program is used to conduct a simulation of balloon trajectories. Balloon locations at fixed times are analyzed for variability. The study concludes that high altitude balloons have some potential for use as surveillance platforms for limited periods of time.

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Analysis of Simulated Drift Patterns of a High Altitude Balloon Surveillance System

by

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Major, United States Army
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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

This study evaluates the potential of high altitude balloons as surveillance platforms. It begins with the mobile Theater Ballistic Missile (TBM) detection problem encountered during the Persian Gulf War of 1990-1991 and it describes a possible scenario using high altitude balloon surveillance systems to locate TBM's accurately enough for effective engagement by strike assets. It presents the history and military use of balloons, and it describes the current state of technology of differing balloon types. Atmospheric circulation impacting balloon drift is presented along with a description of available atmospheric models. Trajectory prediction programs are reviewed and a revised program is used to conduct a simulation of balloon trajectories. Balloon locations at fixed times are analyzed for variability. The study concludes that high altitude balloons have some potential for use as surveillance platforms for limited periods of time.

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I. INTRODUCTION

A. PURPOSE

The Persian Gulf War of 1990-1991 included the firing of more than 80 Scud missiles against Coalition forces and Israel. This was actually the *second* employment of theater ballistic missiles against United States' forces; Germany's use of V-1 and V-2 rockets in World War II was the first. While the military importance of mobile tactical ballistic missiles can be argued, we learned from the Persian Gulf War that such missiles are a threat and they are neither easily detected nor easily destroyed. The purpose of this work is to examine using high altitude balloon systems with sensor payloads to increase our ability to detect and to locate enemy mobile tactical ballistic missile systems.

B. RESEARCH QUESTIONS AND LIMITATIONS

The basic hypothesis of this study is that employing balloons as surveillance platforms at altitudes in excess of 21 kilometers is feasible. Possible research questions include:

- How will balloons drift at higher altitudes?
- Will either "strategic" global circumnavigating balloons or "tactical" theater-employed balloons pass over or nearly over a designated target area to allow some set of these balloons to provide continuous coverage of a target area?

- What are the operational requirements of a balloon surveillance system: e.g. how many systems are needed for coverage of an area and what sensors are best?

This study focuses on the question of balloon drift: that is, where balloon surveillance systems drifting at high altitude would go. The question is further narrowed to balloon location at specific times after launch: ten days, one month, and one year. These locations were used for a statistical analysis of the variance in mean location of drifting high altitude balloons. Thus, the perspective is limited by these discrete and disparate time points. The research presented in this thesis contains no classified information.

II. BACKGROUND: PERSIAN GULF WAR SCUD CAMPAIGN

A. SCUD CAMPAIGN EFFORTS

When Iraq first launched its Scud missiles during the war, conventional wisdom was unanimous: the Scud missiles were militarily insignificant. The reasons were that Iraq had few missile systems and those they had were inaccurate and unreliable. Unfortunately, conventional wisdom concerning the political significance of the Scud attacks was equally unanimous: the attacks could easily bring Israel into the war, with the subsequent result that the Allied Coalition would disintegrate. Given this possibility, the Allies had no choice but to mount a major effort against the Scuds.

It is reported that five percent of the air sorties flown during the war were against the Scuds (Dunnigan, 1992, p. 155), but that figure does not indicate the level of effort actually directed against the Scud threat. The ratio of Scud missions flown out of the total number of *strike* aircraft sorties flown would be much more than five percent. Also, significant non-air assets (Patriot units, launch detection sensors and communication assets) were employed for Scud defense. With this level of effort, Scud operations were degraded, but post-war analysis has indicated that destroying

In sum, zero pressure balloons can be used to reliably

Scud launchers was a difficult job at best because of the complexities involved with detection and engagement.

B. PERSIAN GULF SCUD CAMPAIGN DIFFICULTIES

Initial claims reported by the services and published by the news media during and immediately after the war suggested that Allied forces were extremely effective in detecting and destroying mobile launchers, albeit usually after launch. Upon closer examination, however, it has become clear that we were *not* very effective in doing so. In fact, "there are no confirmed reports of *any* Scud launchers that were destroyed by Coalition forces during the war." (Israel, 1993) We particularly had difficulty finding the launchers, which fired missiles, quickly enough to engage them before they repositioned: sensors in use were inadequate to provide the range, accuracy, and timeliness needed. Costs and operational characteristics of overhead systems, to include remotely piloted vehicles and combat aircraft, precluded continuous, low-cost, low-risk surveillance of an area. Shortly before the Persian Gulf War, the U.S. Army Strategic Defense Command defined several requirements for sensors to detect and to locate mobile missiles. Future sensors must:

- Provide broad area coverage.
- Provide long dwell-time coverage.
- Provide day/night/all-weather coverage.
- Overfly enemy areas.

* Identify potential targets as mobile Scuds.
* Report in near-real time.
* Cue attack assets. (Severance, 1990, pp. 28-29)

What systems can meet these requirements? Our Gulf War experience could be used to argue that the U.S. currently has *no* sensor systems that satisfy all of these needs. However, a free-floating high-altitude balloon surveillance system may be able to do so.

C. BALLOON SURVEILLANCE SCENARIO 1995

Recent Iraqi behavior on several fronts has raised the possibility of military confrontation. Slaughtering of Shiites in the south, heightened tensions directed against the Kurds in the north, Iraqi defiance of United Nations inspection teams, and Iraqi saber-rattling about gaining control of Kuwait, long considered by Iraq as it's 19th province, all indicate an Iraqi intention to break out from underneath stifling U.N. sanctions through military action. United States (U.S.) forces stationed in Saudi Arabia and Israel are prepared, however, with limited defensive units in place and with alerted strike forces on board ships in the Persian Gulf. Seeming to have learned from his failed 1990 invasion of Kuwait, Saddam Hussein daringly launches an all-out attack, simultaneously crossing the border into Kuwait with ground forces and launching Scud missiles at both Saudi Arabia and Israel. Air raid sirens warn friendly personnel to take cover and to don protective masks. Improved Patriot anti-missile rockets streak from the ground to intercept the Scud missiles before their targets can be reached. The dark night sky lights up brightly from the fireworks of intercepts, and the Scud missiles are obliterated by the kinetic energy impacts high in the atmosphere. Friendly personnel breath a little easier as the "all-clear" is sounded and the counterattack against the Scud Transporter Erector Launchers (TELs) begins. Despite an inability to engage the TELs before their departure from the launch area, U.S. forces are able to track the TELs to their "hide" locations using reconnaissance balloons. Upon the launch of the Scuds, the Infrared sensor carried in the balloon payload detects a launch plume, and then triggers a Moving Target Indicator/Synthetic Aperture Radar (MTI/SAR) to point to the launch area. The MTI/SAR focuses upon the vehicle at the launch point, which the SAR processing system identifies as a mobile launcher. The MTI "locks" onto the launcher, tracking it as it repositions from the launch location to a hide location. That location is passed to an in-theater ground station which directs the mobilization of alert aircraft from a carrier to attack the Scud. Smart munitions are subsequently launched to penetrate a sand-covered bunker, where the TEL is destroyed.

III. BALLOON USE AND TECHNOLOGY

A. BALLOON HISTORY

1. Buoyancy and Lift

Archimedes first discovered the principle of buoyancy, that a body immersed in fluid is buoyed up by a vertical force equal in magnitude to the weight of the displaced fluid, in about 240 B.C. The object of a balloon is to displace a large weight of air, thus gaining a buoyant force equal to the weight of the air displaced. Buoyancy is defined by the equation $Bouyancy=(\rho_{air})(Vol_{gas})(g)(1-M_{gas}/M_{air})=(g)(Vol_{gas})(\rho_{air}-\rho_{gas})$ which shows that balloon lift is dependent upon the volume of the balloon (Vol_{gas}) and the difference between the internal "lifting gas" density (ρ_{gas}) and the external air density (ρ_{air}), with g being the acceleration due to gravity. This equation indicates that any gas having a molecular weight less than the molecular weight of air is a potentially useful lifting gas. A comparison of several of these gases and their lifting capability is shown in Table 1. The medium with the smallest molecular weight, hydrogen, provides the greatest lift, with helium next best. (Morris, 1975, pp. IV-4 - IV-7)

TABLE I. LIFT GAS COMPARISON

Gas	Molecular Weight*	Lift Index ($1-M_g/M_a$)
Vacuum	0.000	1.000
Hydrogen	2.016	0.930
Helium	4.003	0.862
Ammonia	17.030	0.412
Water Vapor (Steam)	18.010	0.378
Air	28.960	0.000

* Standard Temperature and Pressure (STP)
M_g = Molecular Weight of Gas
M_a = Molecular Weight of Air

A review of several key characteristics of a few lifting gases reveals why helium is a common choice:

- a vacuum is ideal but obviously difficult to contain.
- hydrogen is readily available and inexpensive, but it is highly flammable.
- helium is readily available, although it is moderately expensive.
- ammonia is toxic in high concentrations and it liquifies easily.
- steam liquifies too readily.
- air is inexpensive but it provides lift only if the density of the air inside the balloon is less than the air outside the balloon (hot air balloons). (Morris, 1975, p. IV-5)

Table II shows examples of the lifting gas required for buoyancy for selected payload weights. It should be noted

TABLE II. HELIUM NEEDED FOR SELECTED PAYLOAD WEIGHTS

Payload Weight (lb/kg)	Balloon Diameter (ft)	Lifting Gas Quantity (ft^3)
100/ 45	45	1520
500/225	130	7600
1000/450	200	15200

that the buoyancy of the balloon must be greater than the weight of the payload for the system to ascend: the balloon will not lift a payload if the buoyant force is less than the forces holding the balloon down. Thus, the weight of the payload suspended below the balloon determines the amount of lifting gas (and the size the weight of the balloon) needed to ensure sufficient buoyancy. (Morris, 1975, pp. IV-4 - IV-7)

2. Balloon Invention and Development

It was not until 1250 A.D. that Roger Bacon suggested filling a vessel with some fluid lighter than air to apply Archimedes' principle in the atmosphere. Cyrano de Bergerac proposed using a belt consisting of glass phials filled with dew to help him ascend to the stars in his book *Voyages to the Moon and the Sun*, published between 1657 and 1662, and then Jacques and Joseph Montgolfier first demonstrated these concepts in November 1782. Wondering why smoke always rose upwards and what would happen if the hot air could be entrapped, they fashioned a lightweight paper bag (their father was a paper manufacturer), and then burned paper underneath. The bag rose to the ceiling of their room. The Montgolfier's repeated their success outdoors, and then demonstrated it with a larger balloon before the Academy of Sciences in Paris. (Glines, 1965, p. 5)

Two centuries of experimentation in shapes, sizes, materials, and lifting gases have followed. Technological advancements have introduced lighter, thinner, stronger, and more versatile balloon envelopes, including plastic films. These changes have resulted in increased buoyancy, decreased gas permeability and longer duration flight. As a result, today's balloons can reliably fly higher and farther than ever before. (Dollfus, 1961, p. 97)

3. Military Balloon Use

Balloons were first used for military purposes during the French Revolution in 1794 at the Battle of Fleurus, where Frenchman Jean Coutelle went 450 meters aloft in a tethered balloon to observe enemy formations and movements. His observations were loudly proclaimed afterwards as key to the French victory. (Glines, 1965, p. 98)

Surveillance balloons were successfully used during the American Civil War with much fanfare, both by the South and the North. Union use was much more successful, led by the much-acclaimed Professor Thaddeus Lowe who made numerous surveillance flights from 1861 to 1863. Professor Lowe's largest contributions were made during the Peninsular Campaign in support of General Hooker. Lowe frequently provided information about the enemy that could not have been obtained without his Balloon Corps of seven balloons and a Navy vessel. Unfortunately, neither Professor Lowe nor his fellow aeronauts were ever commissioned, and the administration of his Balloon Corps was passed from one organization to another. The result was that the Balloon Corps' transportation assets were frequently taken away for other needs so it became impossible to move the equipment: Professor Lowe failed to reach Antietam and Gettysburg quickly enough to provide observation of enemy movements. The difficulties in administrative organization and logistics led to the eventual disintegration of the Corps, with Lowe quitting shortly after Gettysburg. (Glines, 1965, pp. 101-109)

The Franco-Prussian War of 1870-71 saw an increase in balloon use during the siege of Paris, when citizens built 64 balloons which they used to escape and to send messages over the surrounding German troops. By the end of the war, 11 tons of mail and 164 people had been successfully airlifted out. (Glines, 1965, pp. 122-127)

Balloons were used during both World Wars, predominantly in the form of dirigibles, or powered air vehicles. Count Ferdinand von Zeppelin had served with Professor Lowe during the American Civil War and he had become alarmed by the developments made by the French, who had crafted a non-rigid airship which could fly at 11 miles per hour powered by an electric engine. The non-rigid French airship could provide long-range surveillance and carry bombs. The Count built a new rigid airship, named after Zeppelin himself. The Zeppelins were used by the Germans during both World Wars for resupply and bombing, but the hydrogen-filled dirigibles were vulnerable to faster, higher-flying fighter aircraft equipped with machine guns, so their use was limited. (Macksey, 1986, pp. 48-49)

Also during World War II, the Japanese sent 9000 parchment balloons carrying incendiary devices toward the United States. About 1000 balloons reached the North American continent, but the only recorded casualties were five children and a woman at a picnic in Oregon. The U.S. government requested that newspapers *not* report that the balloons were reaching the mainland, and the media blackout led the Japanese to conclude that their program was not worth continuing, despite the fact that their trans-ocean success rate was actually rather good. (Glines, 1965, pp. 143-147)

American military use was prompted by the Japanese program's success, which demonstrated the potential of using jetstream winds to propel balloons. In 1950, the U.S. Air Force began research on a balloon surveillance system to provide reconnaissance overflights of the Soviet Union. This work was done concurrently with the development of the U-2 reconnaissance aircraft and early satellite research. In January 1956, the system was put into operation with balloons containing cameras launched from five locations in Europe. They drifted across Asia at 13.6 kilometers altitude, taking pictures, and while many landed over foreign territory, about 40 were successfully recovered from the Pacific Ocean. The program was discontinued on March 1, 1956 following Soviet protests and a *Washington Post* story on February 10. The program was able, however, to photograph over 1 million square miles of the Sino-Soviet area, at a cost of only $48.49 per square mile. (Davies, 1988, pp. 59-61)

B. CURRENT BALLOON TECHNOLOGY

The three basic types of balloons, zero pressure, superpressure, and sky anchor, are shown in Figure 1 (after Lawrence Livermore). Each type is described below.

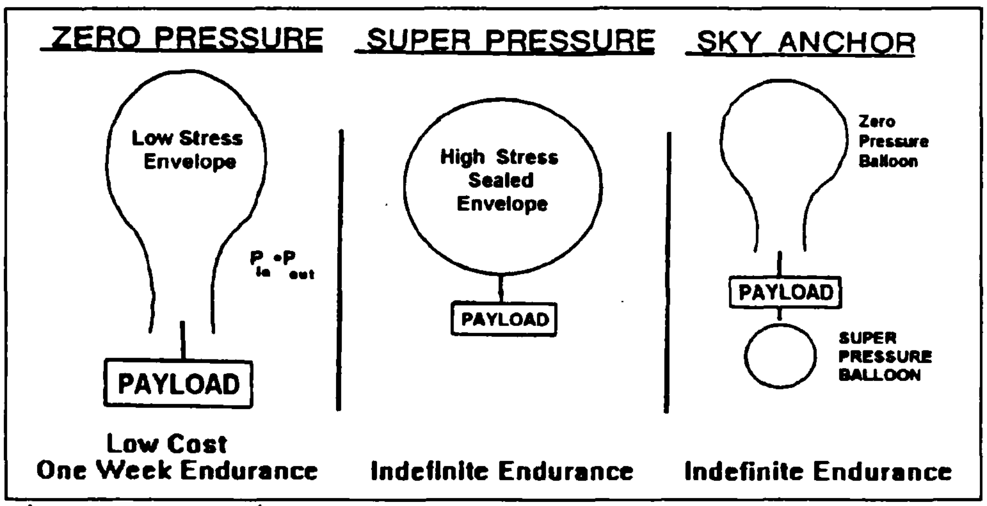

Figure 1. Basic Balloon Types

1. Zero Pressure Balloons

The zero pressure balloon, first built and flown by the Montgolfier brothers, is the type of balloon most used today, for science, military, and recreational purposes. The basic principles of zero pressure balloons have not changed in the 200-plus years since first flight: a non-extensible bag, open at the bottom, is inflated with a gas (usually hot air, helium, or hydrogen) lighter than the surrounding atmosphere. The term "zero pressure" is used because the internal gas pressure is equal to the external gas pressure near the base of the balloon. Slight overpressure is maintained higher inside the balloon above this point in order to retain the shape of the envelope. (Lawrence Livermore, 1990, p. 8)

As previously noted, balloon buoyancy results from the balloon's volume, or atmospheric displacement, following Archimedes principle. From the equation for buoyancy it can be seen that buoyancy increases as the lifting gas becomes less dense; and that buoyancy decreases as the lifting gas becomes more dense or as balloon volume decreases. Since lifting gas pressure, temperature, and density are related by the equation $P=(T_{gas})(\rho_{gas})(B)$ where B is a scaling constant, the altitude of a zero pressure balloon is dependent upon the temperature of the lifting gas. As the gas temperature increases, balloon volume increases and as the gas temperature decreases, balloon volume decreases. In the first case, the balloon becomes more buoyant and it will rise in altitude. In the second case, the balloon becomes less buoyant and it will fall in altitude. An example helps illustrate the cycle a balloon would follow. (Rand, 1992, p. 4)

Assume a zero pressure balloon is floating at an equilibrium altitude. During the day, solar radiation will heat the internal gas, resulting either in increased volume (if the balloon is not fully inflated) or in decreased density (if the balloon is fully inflated, gas is vented, or forced out of the balloon). In either case, the balloon is more buoyant and it will rise to a new density-equilibrium altitude. At night, or in periods of cloudiness, the lifting gas is cooled and it becomes more dense. Pressure remains constant, so the balloon envelope decreases in volume. The decrease in displaced air means the balloon will lose altitude until a new density-equilibrium altitude is reached. (Rand, 1992, p. 4)

A zero pressure balloon may remain at a constant altitude only when gas is vented (if the gas temperature is rising), or when ballast is dropped (if the gas temperature is falling). Even when using these techniques to control zero pressure balloon flight, mission duration of zero pressure balloons is limited to five to seven days, except in rare environmental conditions such as at the poles, because approximately eight percent of the system mass (balloon plus

fixed, but varies in altitude depending upon latitude and time payload plus ballast) must be dropped each night to maintain altitude. (Rand, 1992 p. 5)

Recent developments in automatic ballasting have made it possible to extend zero pressure balloon mission duration at high altitudes in unmanned flight.

> A group of researchers has reported the successful flight of a zero pressure balloon for 40 days above Antarctica. A pressure sensor was used to automatically release two kilograms of ballast whenever the balloon descended to two kilometers below the desired float altitude of 30 kilometers. (Rand, p. 8)

This example illustrates that automatic ballasting may increase mission duration, but the unique environment of Antarctica was a significant factor in this case. Thus, it remains to be seen if automatic ballasting would increase mission duration so dramatically at mid-latitudes.

Zero pressure balloons can carry several thousand pounds of payload to altitudes as high as 130,000 feet because there is very little stress on the balloon envelope.

> In December 1990, a 29.47 million cubic foot helium balloon carried a 3750 pound payload to an altitude of 130,000 over Antarctica. During its nine day mission, the balloon circumnavigated the Antarctic continent (more than 4,000 miles) and landed its payload only 113 miles from the launch point. (Winzen, 1991, p. 2)

The condition of 24 hours per day of sunlight minimized ballast requirements, gas venting, and altitude changes, which maximized the mission duration of the balloon.

In sum, zero pressure balloons can be used to reliably lift large payloads to significantly high altitudes, but only for about a week at mid-latitudes.

2. Superpressure Balloons

Superpressure balloons are similar to zero pressure balloons, except that the envelope is sealed at the bottom to create a pressurized envelope so no gas can escape. Even though the internal pressure varies slightly due to changes in internal gas temperature, these balloons remain at a constant volume because of the strength of the envelope. This constant envelope volume results in altitude stability at a constant density altitude where system weights are in equilibrium with the surrounding atmosphere. The high internal pressures require a film envelope that is thin yet strong, lightweight, free of pinholes, and impermeable to gas diffusion. (Winzen, 1991, p. 2)

The first superpressure balloon was flown shortly after Montgolfier's first flight, but significant research of superpressure balloons was not pursued until polyethylene, a synthetic material with the physical properties necessary for superpressure envelopes, was developed during World War II. Polyethylene was tested extensively as the envelope in zero pressure balloons during the 1950's, then tried with superpressure balloons beginning in 1961. From 1968 through 1970, numerous superpressure balloon flights were conducted by

month database of properties in four dimensions: latitude,

the National Center for Atmospheric Research (NCAR). Over 200 balloons were flown at altitudes of 16-24 kilometers for durations of up to 744 days, with altitude deviations of less than 100 meters. Payloads were less than one pound. (Lawrence Livermore, 1990, p. 52)

In 1973, the National Scientific Balloon Facility (NSBF) conducted Project Boomerang:

> Two 20 meter diameter polyester superpressure spheres were successfully flown from Australia, with payloads of 52 kilograms and 46 kilograms respectively. Both flights circumnavigated the globe: one flight lasted 36 days and was recovered within 16 kilometers of the launch point; the other lasted 212 days. [recovery status not stated] (Rand, 1992, p. 9)

Multiple superpressure balloon flights were conducted during the 1970's by various organizations with mixed results. As attempts were made to scale the balloons to larger sizes, it was found that the materials being used had the propensity for catastrophic failure from flaws that developed either in manufacture or in handling. Thus, superpressure ballooning research was reduced while zero pressure balloon research was emphasized. (Winzen, 1991, p. 1)

Throughout the 1970's and 1980's, Mylar was the best material available for superpressure balloons...indeed the small Mylar balloons that may be bought at any number of gift or party stores today are really superpressure balloons. Unfortunately, Mylar develops pinholes during manufacture, so it is a poor gas barrier, and Mylar superpressure balloons are limited to payloads less than 100 pounds at high altitudes. (Winzen, 1991, p. 1)

Recognizing the potential applications of stable high altitude balloons, the Defense Advanced Research Project Agency (DARPA) sponsored a Small Business Innovative Research (SBIR) program to develop a superpressure system with better materials. The best material, determined from a 1991 study by Winzen International of San Antonio, Texas, is a biaxially oriented nylon film which has the strength, weight, and gas impermeability properties desired. Synthetic films are usually stressed in only one direction during manufacture but this material is a nylon film that is stressed in two directions. This process orients the film's molecules so that the material is as strong laterally as it is longitudinally. Research has shown that the altitude of a balloon made of this material will vary from day to night by only 200 meters, independent of the size of the balloon. Furthermore, permeability measurements demonstrate that the life of this balloon should exceed four years. (Rand, 1991, pp. 1-1 - 1-3)

Two test flights have been conducted using this biaxially oriented nylon material. In August 1992, a nine meter diameter balloon was launched in Utah, carrying a 14 kilogram payload to an altitude of 20 kilometers. In October 1992, a 23 meter diameter balloon carried a 23 kilogram payload to an altitude of 33 kilometers. Both balloons maintained their design altitudes until they were destroyed by command. Test flights of superpressure balloons with this material continue with the following goals:

- Within one year; fly a 23 kilogram payload to 36 kilometers for 30 days.
- Within 18 months; fly a 450 kilogram payload to 36 kilometers for 30 days. (D. Brown, 1992, p. 56)

3. Sky Anchor Balloons

The sky anchor is a hybrid system combining zero pressure balloons and superpressure balloons in an attempt to stabilize zero pressure altitude excursions and to achieve extended flight. The idea is to fly two balloons together to gain lift capacity with the zero pressure balloon and to gain altitude stability with the superpressure balloon by using it as air ballast. As the zero pressure balloon ascends due to warming, the superpressure balloon becomes heavier than the surrounding air, preventing the entire system from ascending to an altitude that would require gas to be vented from the zero pressure balloon. Cooling the gas in the zero pressure balloon returns the system to its original equilibrium point. (Lawrence Livermore, 1990, p. 9)

Sky anchor systems have been constructed and flown, but with little success. The challenges involved in handling and launching two balloons simultaneously are significant, and even various configurations of balloons and payloads have produced limited results. The theory of operation at altitude is fine; the difficulty lies in getting the system to an equilibrium altitude. (Winzen, 1991, p. 3)

The NSBF conducted a series of tests with sky anchors in the late 1970's. Numerous launch problems were experienced, but one system carrying 227 kilograms was able to remain at about 36 kilometers altitude for four days. Unfortunately, altitude variations of up to six kilometers were frequent. (Lawrence Livermore, 1990, p. 52)

The most famous sky anchor system is the EarthWinds project, which in recent years has made repeated attempts to circumnavigate the globe. The crew's attempts have not been successful, and they have encountered significant skepticism from the scientific community and the media throughout. Overall, the sky anchor's poor record make it an unlikely candidate for military use. (S. Brown, 1992, pp. 80-126)

C. SUMMARY OF BALLOON USE AND HISTORY

A variety of balloons have been used effectively for a number of purposes in military conflicts since their invention by Frenchmen in 1782. Two types of balloons, zero pressure and superpressure, seem to offer good potential for future military use. Currently, zero pressure balloons are capable of carrying large payloads for up to a week while superpressure balloons are capable of smaller payloads for many weeks or even years.

IV. ATMOSPHERIC CIRCULATION AND MODELING

Central to any discussion of the use of free-floating balloons is an understanding of atmospheric dynamics. This section describes the differences in the earth's atmospheric circulation based upon altitude, latitude, and time of year.

A. ATMOSPHERE STRUCTURE

Meteorologists conventionally divide the atmosphere into four layers based on the vertical gradient of temperature. These layers, as shown in Figure 2, are the troposphere, stratosphere, mesosphere, and the thermosphere. Temperature

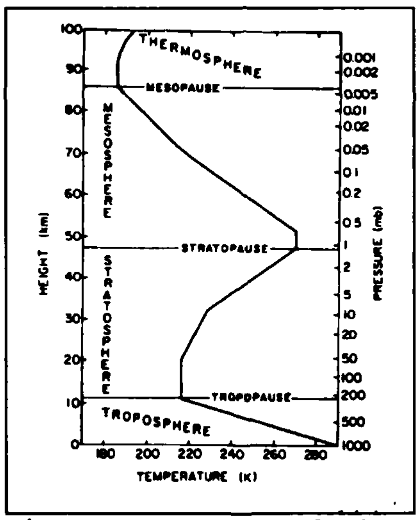

Figure 2. U.S. Standard Atmosphere Temperature Profile, 1976

generally decreases with height in the troposphere and in the mesosphere, and it generally increases with height in the stratosphere and in the thermosphere. The troposphere accounts for almost 85 percent of the total mass of the atmosphere, and it accounts for virtually all atmospheric water vapor. The tropopause, which separates the troposphere and the stratosphere, is a level of temperature minimum which varies in height from about 15 kilometers at the equator to nine kilometers at the poles. The stratopause is a level of temperature maximum near 50 kilometers which separates the stratosphere and the mesosphere. The mesosphere is bounded above by the mesopause, a level of temperature minimum similar to the tropopause at about 80 kilometers. (Andrews, 1987, p.3)

In addition to temperature, three other physical properties characterize the atmosphere: pressure, density and velocity. Pressure is defined as the amount of force applied over a surface or force per unit area, which can be either the earth's surface or an air parcel. Pressure is measured in either millibars (mb) or in kilopascals (kPA), with one bar equal to 14.5 pounds per square inch. Standard sea level pressure (STP) equals 1013.25 mb or 101.325 kPa. Air pressure decreases with altitude; several altitude-pressure reference points are provided in Table III. Density is the amount of a substance per unit measure or mass at standard pressure and temperature. The air density also decreases with altitude as

TABLE III. ALTITUDE-PRESSURE REFERENCE POINTS

ALTITUDE ft & (km)	PRESSURE lb/ft^2 & (mb)
Sea Level	2116 (1013)
50,000 (15.2)	242 (116)
70,000 (21.3)	93 (44)
100,000 (30.5)	23 (11)
120,000 (36.6)	11 (5)
140,000 (42.7)	5 (2)

both pressure and temperature decrease. Velocity is a measure of wind speed relative to the ground, measured in meters per second. As noted in the discussion on balloon buoyancy, all three of these physical quantities have an impact upon balloon lift and drift. (Holton, 1979, p.1)

B. ATMOSPHERIC CIRCULATION

1. Fundamental Motion Forces

The motions of the atmosphere are governed by the fundamental laws of fluid mechanics and thermodynamics: the laws of conservation of mass, momentum, and energy. The primary forces which cause atmospheric motion are the pressure gradient force, the gravitational force, and friction. Additionally, one "apparent" force also acts upon the atmosphere to cause motion: the Coriolis force. (Holton, 1979, p.5-17)

An object or air parcel accelerates in the direction of the applied pressure gradient force, as shown in Figure 3.

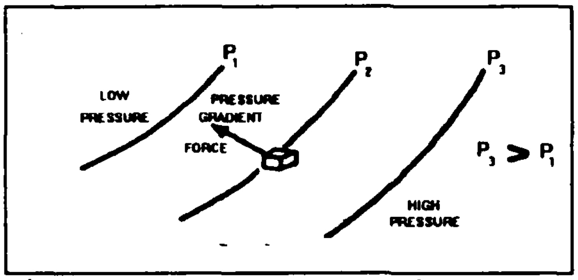

Figure 3. Pressure Gradient Force

The pressure gradient force is proportional to the *gradient* of the pressure field, not to the pressure itself. This force is active through the entire atmosphere. (Holton, 1979, p.5-7)

Tropospheric and stratospheric circulation are both strongly influenced by the Coriolis force, which is an apparent force or effect which accounts for the rotation of the earth. The rotation of the earth imparts spin to an air particle in the atmosphere, which causes the air particle to have an angular momentum, or coriolis acceleration, with respect to the earth. As shown in Figure 4 (after Lawrence

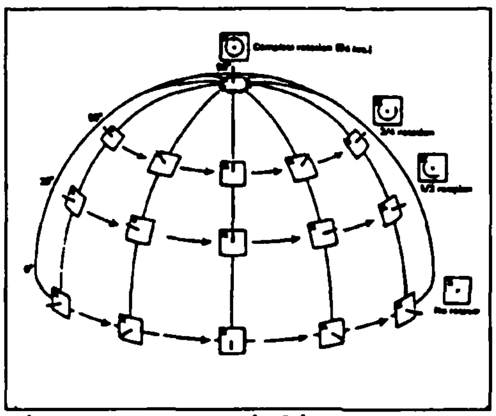

Figure 4. Coriolis Acceleration

Livermore), this angular momentum varies with latitude, with no Coriolis acceleration for horizontal motion at the equator. As the air particle is accelerated by the pressure gradient force, the Coriolis acceleration will increase until it reaches a balance as shown in Figure 5 (after Lawrence

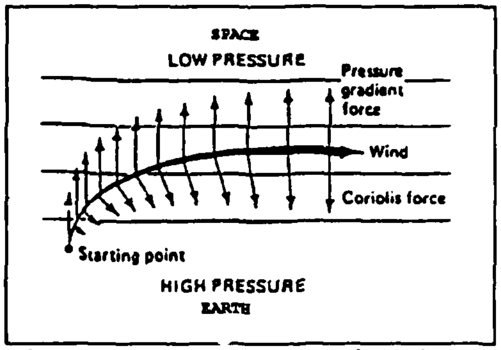

Figure 5. Geostrophic Winds

Livermore). The balance causes "geostrophic" winds that flow parallel to the isobars at a speed proportional to the pressure gradient and inversely proportional to the sine of the latitude. (Lawrence Livermore, 1990, p. 25)

Friction is important near the surface of the earth, where atmospheric motion is retarded by contact with the earth's surface. Friction thus influences circulation in the lower troposphere but its only effect at higher altitudes is indirect through the interaction of tropospheric eddy motions with the lower stratosphere. (Holton, 1979, pp. 296-298)

2. Observed Circulation

a. Zonally Averaged Circulation

All references in atmospheric circulation studies create a distinction between the longitudinally averaged flow, which is either zonal mean flow or meridional mean flow, and the deviations from these means, or eddies. Zonal mean winds are parallel to the equator, while meridional mean winds are perpendicular to the equator. This section describes stratospheric circulation in terms of zonally averaged circulation.

b. Observed Circulation Patterns

A combination of radiosonde data, rocketsonde data, and, more recently, remote temperature soundings from satellites, have provided meteorologists with a much clearer picture oi stratospheric dynamics than ever before. At this time, the study of upper atmosphere circulation patterns has revealed that there are only a handful of general cases of circulation, and that upper atmosphere circulation is influenced by the annual solar cycle.

> The net radiative heating distribution has a strong seasonal dependence with maximum heating at the summer pole and maximum cooling at the winter pole. The Coriolis torque exerted by this meridional flow generates mean zonal easterlies (from the east) in the summer hemisphere and westerlies in the winter hemisphere. (Andrews, 1987, p. 6)

The circulation patterns vary gradually from month to month during the annual cycle and they recur regularly. The *general* categories of stratospheric circulation are listed below:

- the extratropical, or non-equatorial, pattern is westerly zonal-mean winds in the winter hemisphere, and easterly zonal-mean winds in the summer hemisphere. Figure 6 shows zonal mean winds in meters per second for solstice conditions with W and E designating centers of westerly (positive, from the west) and easterly (negative, from the east) winds, respectively. (Andrews, 1987, p. 8)

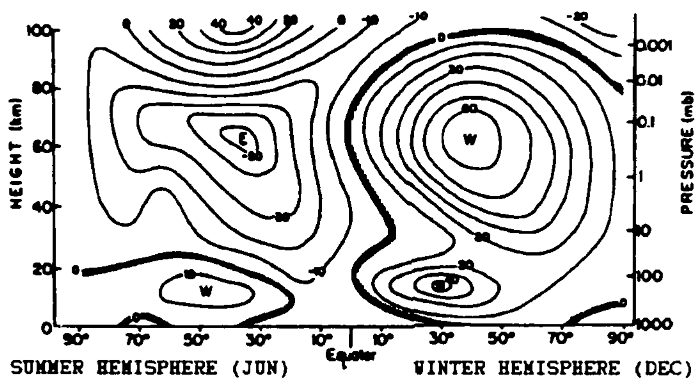

Figure 6. Zonal Mean Winds for Solstice Conditions

- stratospheric sudden winter warmings in the Northern Hemisphere lead to mean-flow deceleration and even to a reversal of the winds to easterly. (Andrews, 1987, p. 259)

- the equatorial pattern is an alternating pattern of eastward and westward winds that repeat at intervals varying from about 22 to 34 months, with an average period of about 27 months (though there is a six month cycle at higher levels). (Andrews, 1987, p. 313)

- the transition between the Northern and the Southern Hemispheres at the equinoxes results in weak mean zonal westerlies in both hemispheres. (Andrews, 1987, p. 6)

An important point to observe from Figure 6 is that wind speed seems to be at a minimum at approximately 20 kilometers altitude. This region of minimum winds is not fixed, but varies in altitude depending upon latitude and time of year. Figures 7-10 show that altitudes of 30-40 kilometers appear to be the most promising for balloon surveillance operations.

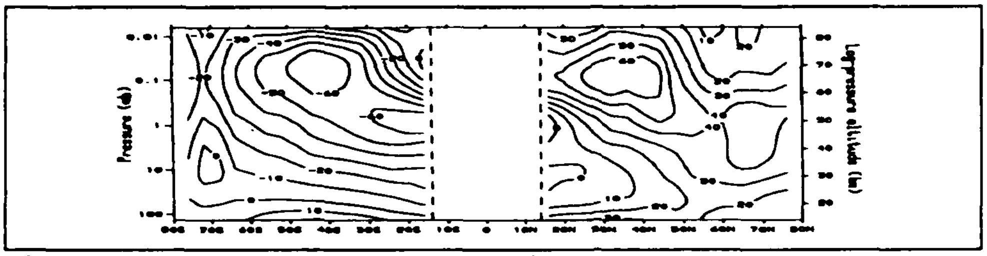

Figure 7. January Zonal Mean Winds

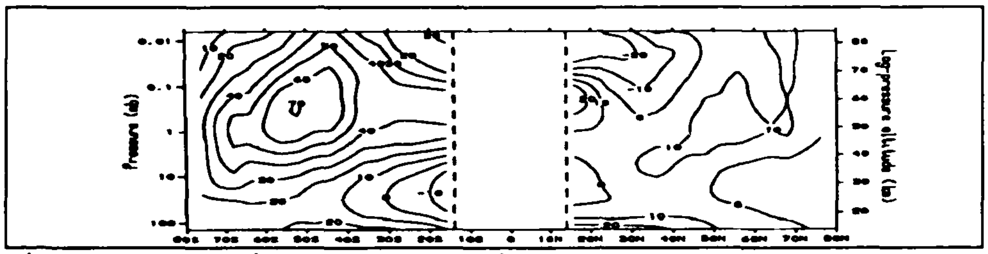

Figure 8. April Zonal Mean Winds

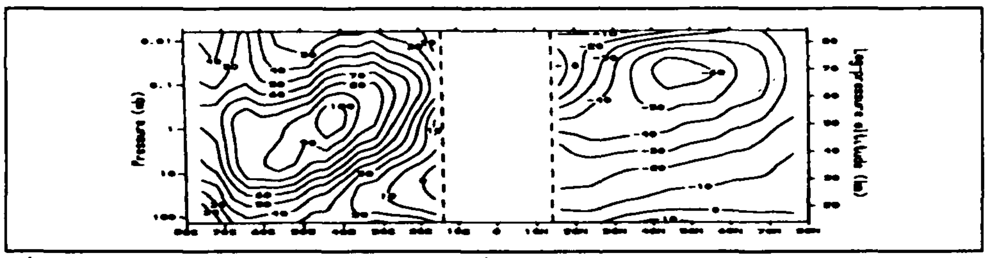

Figure 9. July Zonal Mean Winds

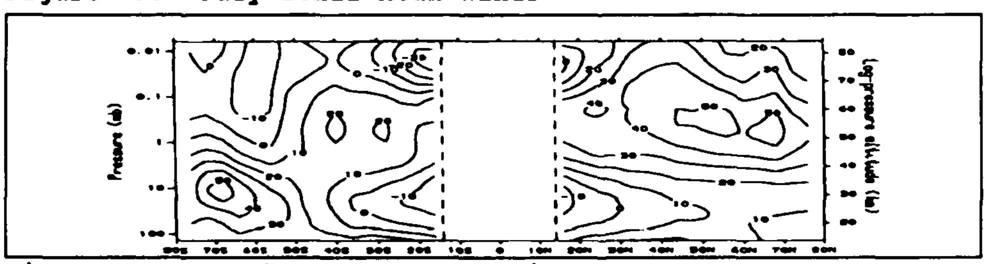

Figure 10. October Zonal Mean Winds

5. Real World Meaning of Results

C. ATMOSPHERIC CIRCULATION MODELING

The majority of atmospheric circulation models that have been developed are tropospheric models, primarily because of the need to understand the earth's climate and weather. However, much more work dealing with the stratosphere has been done in the last 20-30 years because of concerns about the earth's ozone layer. Circulation models fall into two categories: those based on simulated physical processes and those based on historical data.

One general circulation model based on a simulation of the physical processes is the SKYHI model, developed by the Geophysical Fluid Dynamics Laboratory at Princeton. SKYHI is considered to provide the most complete representation of the middle atmosphere: it has 40 prediction levels extending from the surface of the earth to about 80 kilometers and the predicted fields include wind, temperature, water vapor and surface pressure. (Andrews, 1987, p. 422)

A model based on historical atmospheric data is the Global Reference Atmosphere Model, or GRAM, an empirical FORTRAN computer simulation of the earth's atmosphere developed at Georgia Tech. GRAM, which is currently the responsibility of the National Aeronautical and Space Administration (NASA), uses data from several sources and over several years to compute monthly averages of atmospheric properties, including wind speed and wind direction. GRAM provides a worldwide, 12-

month database of properties in four dimensions: latitude, longitude, altitude, and time of year. There are two key points to keep in mind when using the GRAM. The first is that the GRAM contains statistically *averaged* data: it provides mean wind speed and direction, with standard deviations, for an *entire month* for a given combination of latitude, longitude, and altitude. Secondly, insufficient data for the Southern Hemisphere caused the designers of the GRAM to represent it with a six month displacement of Northern Hemisphere data. (Hawkins, 1991, pp. 1-18)

This second shortcoming of GRAM was alleviated in its latest version, produced in 1990 and appropriately called GRAM-90. GRAM-90 incorporates extensive new data, mostly gathered by satellites, to utilize actual data from the Southern Hemisphere for each month. Like GRAM, GRAM-90 provides mean values, but it also produces "perturbation" values which are slightly different from the mean values. These perturbation values are drawn from the historical record of winds to provide a broad perspective of atmospheric conditions at a given point. (Jeffries, 1993)

Other models are available, but the models just described demonstrate the basic types and capabilities of circulation models. Of these, SKYHI is more of a "prediction" model, while GRAM, and the GRAM-90 in particular, provide useful databases for statistical analysis.

narrow over short periods of time, a distribution analysis

D. SUMMARY OF ATMOSPHERIC CIRCULATION AND MODELING

To sum up, it should be noted that stratospheric circulation is different than that of the troposphere and that models which describe atmospheric circulation are available. Stratospheric winds are *fairly* stable, *relatively* light and their circulation patterns vary during the year as a result of the annual solar cycle. However, even though wind circulation seems favorable for military balloon operations, it remains to be seen if the circulation patterns will cause a free floating balloon to "orbit" the earth or if they will cause them to congregate in localized patterns. This is the subject of the next chapter.

V. TRAJECTORY PREDICTION

Generally speaking, people reject out of hand the idea of using free-floating balloons for military surveillance or communications missions because of the uncertainty involved. Balloon trajectories cannot be predicted accurately like satellite orbits, nor are balloons tightly controlled like aircraft. However, the variability of free-floating high altitude balloon trajectories is not extreme: as described in Chapter IV, winds in the upper stratosphere may be stable enough to provide fairly constant trajectories. Balloons travelling in these winds may even be able to provide *better* coverage of an area than low-earth orbiting satellites because of longer time over target. Thus, a statistical analysis of the variability of balloon trajectories in the upper stratosphere may be useful either to confirm or to refute conventional wisdom about the potential of free-floating balloons.

A. BALLOON TRAJECTORY PREDICTION PROGRAMS

A study of relevant literature reveals that very little work has been done in the area of balloon trajectory prediction, with the exception of predicting *vertical* trajectories of weather balloons. The paucity of study led DARPA to sponsor Coleman Research Corporation (CRC) to develop a Balloon Drift Pattern Simulation (BDPS). DARPA personnel were interested in exploiting high-altitude, expendable balloons for a variety of military missions, and they needed a model to predict how balloons would drift in order to assess the feasibility of several concepts.

In Phase I of an SBIR project, CRC wrote an upper-atmosphere drift pattern simulation for execution and display output on VAX computers, demonstrating the technical feasibility of predicting drift patterns using a digital computer simulation. In Phase II of the SBIR, DARPA required CRC to develop a Macintosh-based version of the BDPS. The intent was to build a desk-top, deployable aid that would enable a theater-level commander to assess how to employ balloon systems for either communications or surveillance missions. (Hawkins, 1991, p. 1-18)

The BDPS is a time-step simulation which draws upon a database of wind tables to compute a balloon drift pattern. This database can be actual wind tables (either archived wind data or forecast wind data) or a climate model. The user chooses the database based on his needs: archived and forecast data (such as the Navy's NOGAPS data from the Fleet Numerical Oceanography Center) is only available to an altitude of about 30 kilometers (10 millibars). If the simulation calls for drift patterns above this altitude, the forecast data must be extrapolated or a climate model must be used. As described in Chapter IV, several climate models are available for use.

Since BDPS is used on a Macintosh, it is *mostly* user-friendly, but it is quite large (39 Megabytes) and it is also very slow: it takes about 10 minutes to calculate and to display just 24 hours of a trajectory. (Hawkins, 1991, p. 1-18)

The combination of the BDPS program and the DARPA study on superpressure balloons demonstrated the potential of balloon systems. Unfortunately, the personnel at DARPA who were interested in such systems rotated to other duty stations and the balloon system ideas have not been pursued.

The GRAM-90 is not a drift prediction model in that it provides atmospheric data for a specific point of altitude, latitude, longitude, and date. However, modifications were made to the program so that it could be used as to describe balloon drift. Specifically, source code was added to convert the wind direction and wind speed for a designated time step into a drift vector to apply to the initial balloon start point (altitude, latitude, longitude, and date). This vector was used to compute a new balloon location. This new location was then treated as another start point input for the model, which produced the atmospheric conditions at the new location. This wind vector and time step process was repeated for a year and the balloon's location was recorded intermittently for future analysis. The design, use and analysis of this simulation are described in more detail in the next section.

B. PREDICTION SIMULATION DESIGN

The basic design of the simulation was to use the modified GRAM-90 as a time-step simulation of balloon movement resulting from winds at altitude. By changing the input seed to a random number generator used in the unmodified program, varying trajectories were produced. The seed was randomly changed for each replication of a given set of initial conditions (latitude, longitude, altitude and month). Balloon locations were recorded as desired to provide data for a determination of the variability of the trajectories.

1. Physical Equipment

The modified GRAM-90 was used on the Naval Postgraduate School's Amdahl mainframe computer emulating an IBM 3270. Data analysis was completed using the Minitab statistical package, also on the mainframe.

2. Hypotheses

The null hypothesis was that the trajectories of free-floating balloons drifting at 36 kilometers altitude would *not* follow regular or repeating patterns of drift. The alternative hypothesis was that these balloons would indeed follow regular or repeating patterns of drift.

3. Assumptions

- GRAM-90 as modified is a valid balloon drift prediction simulation. Since a balloon will achieve equilibrium with the winds surrounding it, the assumption is that a one hour time step is sufficiently small to accurately describe the balloon's trajectory using only the wind speed and wind direction outputs from the model.

- GRAM-90 is a valid atmospheric model of winds at altitude. Although the GRAM-90 has averaged data, the assumption is that drawing the standard deviations, or perturbation values, from many years of data ensured validity. In fact, the wind speeds varied considerably more than expected, although they tended to average out over time.

- Balloon altitude is constant. The vertical position of the balloon was assumed to be unchanging in an attempt to study the horizontal trajectory of a drifting balloon.

- Balloon ascent is assumed to be instantaneous to a point directly overhead the starting latitude and starting longitude. GRAM-90 describes atmospheric conditions at a specific point; the available portion was conditions *above* 30 kilometers. Tropospheric winds which would have an effect on the horizontal position of a balloon during ascent were not be modeled for this simulation.

4. Measure of Balloon Drift

Balloon location was measured in latitude and longitude after ten days, 30 days, and 360 days. Latitude was in a form suitable for analysis in its range from -90° to +90°. Longitude was not in a suitable form: in normal mathematical operations -179 is 178 units away from +179, yet there is a difference of only two degrees between -179° and +179°. Thus, it was necessary to convert longitude from absolute degrees to a degree *difference* from the starting longitude.

5. Statistical Design of Simulation

Table IV lists the simulation's variables and values, which were chosen since atmospheric conditions vary with each.

TABLE IV. SIMULATION VARIABLES AND VALUES

Month	Latitude	Longitude
March	45° S	90° E
June	0°	90° W
September	45° N	
December		

The values of each variable are not all-inclusive but were chosen to provide a cross-section for each factor. Each of the 24 possible combinations of these variables was used to specify the initial conditions for multiple replications of the simulation.

C. PREDICTION SIMULATION DATA ANALYSIS

Data was separated into three categories for analysis: ten days; 30 days; and 360 days. Data in each category was checked for normality and uniformity, and then the variance of the means and medians was compared through a variety of statistical tests. Lastly, the three categories were compared to each other for a broader perspective.

1. Balloon Location After Ten Days

Data from all 24 sets of initial conditions in this category was found to be neither normal nor uniform. Latitude of a balloon after drifting ten days *does* follow a pattern but longitude does not. Despite a lack of normality, an Analysis of Variance (ANOVA) for latitude shown in Table V was used to indicate which factors were significant. Since the data was not normal, the numerical values derived from the ANOVA were not valid. The ANOVA shows that ending latitude was dependent upon starting latitude and month, but not on starting longitude ($P = 0.547$). Ending longitude was also dependent upon starting latitude and month, and it was dependent upon starting longitude only for Equator launches.

TABLE V. LATITUDE ANALYSIS OF VARIANCE AT TEN DAYS

```
MTB > anova 'lat' = 'month'!'slat'!'slong'

Factor      Type Levels Values
MONTH      fixed      4      3      6      9     12
SLAT       fixed      3    -45      0     45
SLONG      fixed      2    -90     90

Analysis of Variance for LAT

Source                  DF          SS          MS        F        P
MONTH                    3       50405       16802   521.40    0.000
SLAT                     2     1158260      579130  1.8E+04    0.000
SLONG                    1          12          12     0.36    0.547
MONTH*SLAT               6       15835        2639    81.90    0.000
MONTH*SLONG              3        5394        1798    55.79    0.000
SLAT*SLONG               2        4755        2377    73.77    0.000
MONTH*SLAT*SLONG         6        5796         966    29.98    0.000
Error                  720       23202          32
Total                  743     1263658


LAT   = ENDING LATITUDE                 DF = Degrees of Freedom
MONTH = START  MONTH                    SS = Sum of Squares
SLAT  = START  LATITUDE                 MS = Mean Square
SLONG = START  LONGITUDE                F  = F Test Statistic
                                        P  = P-Value
```

Since longitude was found not to be a significant factor, data was analyzed further in the configuration shown in Table VI.

TABLE VI. INITIAL CONDITION SETS

SET NUMBER	MONTH	LATITUDE	LONGITUDE
1	MAR	45^o S	90^o E/90^o W
2	MAR	0^o	90^o E/90^o W
3	MAR	45^o N	90^o E/90^o W
4	JUN	45^o S	90^o E/90^o W
5	JUN	0^o	90^o E/90^o W
6	JUN	45^o N	90^o E/90^o W
7	SEP	45^o S	90^o E/90^o W
8	SEP	0^o	90^o E/90^o W
9	SEP	45^o N	90^o E/90^o W
10	DEC	45^o S	90^o E/90^o W
11	DEC	0^o	90^o E/90^o W
12	DEC	45^o N	90^o E/90^o W

Figure 11 shows mean latitudinal displacement distances for this category where balloons remained within about eight degrees of their starting latitude. This deviation varies by

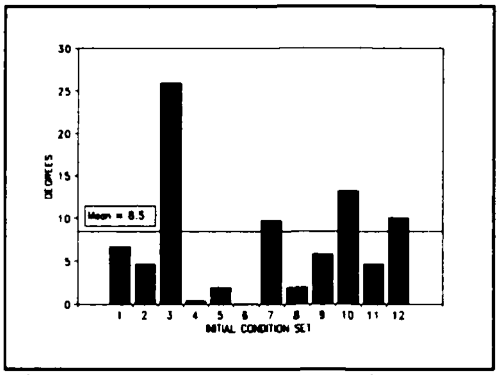

Figure 11. 10 Day Latitude Displacement

month, with June (initial condition sets 4-6) being the month when the balloons remained closest to the starting latitude and March (sets 1-3) having the largest deviation.

2. Balloon Location After 30 Days

As in the ten day category, data was found to be neither normal nor uniform. Figure 12 shows mean latitudinal

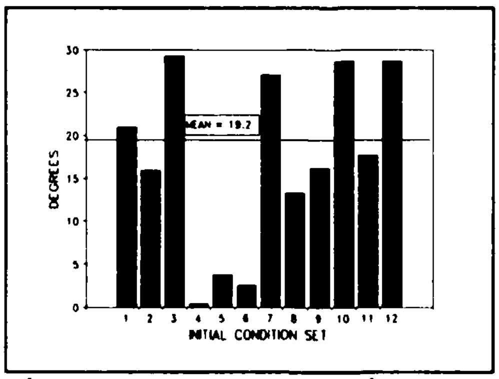

Figure 12. 30 Day Latitude Displacement

displacement distances for this category, where balloons drifted within about nineteen degrees of their starting latitude. The deviations were smallest again in June. ANOVA indicated that balloon location after 30 days is dependent upon all factors: month, starting latitude, and starting longitude.

3. Balloon Location After 360 Days

Figure 13 shows mean latitudinal displacement for balloons after 360 days of drift: the balloons usually drifted

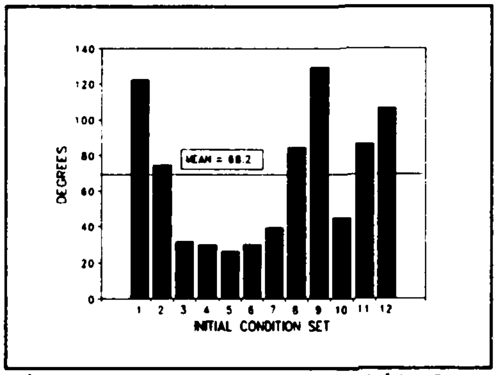

Figure 13. 360 Day Latitude Displacement

over sixty degrees from their starting latitude. In fact, Table VII shows that balloons tend to drift toward the poles after almost a year. Once again, the data is neither normal nor uniform. The ANOVA for latitude again indicates that ending latitude is not related to starting longitude, but it is dependent upon both starting latitude and the starting month. Most often, balloons launched from North of the Equator

TABLE VII. 360 DAY LATITUDE DISTRIBUTION

```
Histogram of LAT   N = 744
Each * represents 10 obs.

Midpoint   Count
     -80     350 ***********************************
     -60       9 *
     -40       8 *
     -20      36 ****
       0      26 ***
      20      38 ****
      40      19 **
      60      88 *********
      80     170 *****************
```

tended to drift toward the North Pole, and balloons launched from South of the Equator tended to drift toward the South Pole, although there were anomalies where balloons drifted toward the pole opposite their launch hemisphere.

4. **Comparison of Categories**

It can be seen from all three categories that balloons follow regular or repeating patterns in their latitudinal displacement. Further, as might be expected, the displacement from start latitude increased over time. In all three categories, ending latitude was found to be dependent upon starting latitude and month but not on starting longitude. Starting longitude was found not to be a significant factor, except for an Equator launch in the 30 day category.

5. Real World Meaning of Results

The most important finding of the analysis of the data is that balloon drift patterns over ten days follow fairly narrow patterns. An examination of the distances involved illustrates this importance. After ten days, most balloons completed between one-half global circumnavigation and one complete global circumnavigation. The mean difference in latitude at that time was 8.5 degrees, or a ground distance of approximately 950 kilometers. At an altitude of 36 kilometers, the balloon has a line-of-sight footprint on the ground of 730 kilometers radius or 1460 kilometers diameter. Thus, even with a drift distance of 950 kilometers, the balloon retains visibility of a sizable portion of the original footprint, although that footprint obviously would have shifted dramatically longitudinally. A "theater" surveillance balloon which would be employed for less than ten days, perhaps even for as little as one or two days, would have even less drift.

VI. CONCLUSIONS

A. BALLOON SURVEILLANCE SYSTEM FEASIBILITY

The narrow drift patterns of balloon flights of ten days support the idea of "theater" or "tactical" high altitude surveillance balloons, probably with flights of three days or less. Such balloon systems could be recovered by steerable parachute or mid-air "snatch" after theater transit. With a ground speed much less than that of satellites and if outfitted with appropriate sensors, they would provide a surveillance system that could overfly enemy areas to identify and to locate mobile ballistic missile systems to be attacked. Such a system would provide a significant improvement in the United States' missile defense posture.

B. AREAS FOR FUTURE STUDY

There are many potential areas for further study with this subject. One suggestion would be to actually launch balloons to check the validity of the simulation model. Also, other simulations would be valuable. It is recommended that the simulation be replicated at different altitudes. This study looked only at 36 kilometers; it would be helpful to examine balloon drift at a variety of altitudes to examine the variance based on altitude. Additionally, and perhaps more importantly, since it appears that drift patterns are fairly narrow over short periods of time, a distribution analysis similar to this study should be completed with balloon locations recorded at intervals less than ten days. Another area to be looked at would be a time series analysis of balloon location to try to get more of a "continuous" perspective rather than the discrete approach used here. Many other subjects for study fall under the heading of operational requirements of a high altitude balloon system: sensor selection, payload configuration, power requirements and sources, C3I architecture, and concept of operations.

APPENDIX (MODIFIED GRAM-90 SOURCE CODE)

The Scientific Model (SCIMOD or SCIM) is only a fraction of GRAM-90, but since it is the only section in which modifications were made for the balloon trajectory, it is the only portion enclosed for future reference. The entire GRAM-90 may be obtained from NASA Marshall Space Flight Center.

```
      SUBROUTINE SCIMOD(NPOP)
C.....COMPUTES VALUES P,D,T,U,V AND SHEAR DUH,DVH FROM INPUT AND
C         ARRAYS IN COMMON PDTCOM.  INPUT TO SCIMOD IS
C         G = GRAVITY AT POSITION       RI = RADIUS AT HEIGHT H
C         PHIR = LATITUDE (RADIANS)     THETR = LONGITUDE (RADIANS)
C         F10 = F10.7 SOLAR FLUX        F10B = MEAN F10.7 FLUX
C         AP = SOLAR-GEOMAGNETIC A SUB P INDEX
C         MN/IDA/IYR = DATA (IYR = FULL YEAR-1900)
C         IHR MIN = TIME                H1 = PREVIOUS HEIGHT
C         PHI1R = PREVIOUS LATITUDE     THET1R = PREVIOUS LONGITUDE
C         RP1,RD1,RT1 = PREVIOUS RANDOM PERTURBATIONS
C         SP1,SD1,ST1 = PREVIOUS RANDOM STANDARD DEVIATIONS (SIGMAS)
C         RU1,RV1 = PREVIOUS RANDOM WINDS
C         SU1,SV1 = PREVIOUS RANDOM WIND SIGMAS
      COMMON/IPRTP/ IPRT,NLIMIT
      COMMON/IOTEMP/IOTEM1,IOTEM2,IUS,DD,XMJD,PHI1,PHI,
     .NSAME,RP1L,RD1L,RT1L,SP1L,SD1L,ST1L,RU1L,RV1L,SU1L,SV1L,
     $ MN, IDA, IYR, H1, PHI1R,THET1R,G,RI,H,PHIR,THETR,F10,F10B,AP,
     .    IHR,MIN,NMORE,DX,HL,VL,DZ,B,EPS,IOPP,LOOK,IET,FLAT,
     1RP1S,RD1S,RT1S,RU1S,RV1S,SP1S,SD1S,ST1S,SU1S,SV1S,
     2UDS1,VDS1,UDL1,VDL1,UDS2,VDS2,UDL2,VDL2
      COMMON /PDTCOM/IU4,MONTH,IOPR,
     . PSP(15,19,18),DSP(15,19,18),TSP(15,19,18),USP(15,19,18),
     .                VSP(15,19,18),
     . PG(21,19),DG(21,19),TG(21,19),UG(21,19),
     . PAQ(17,5),DAQ(17,5),TAQ(17,5),UAQ(17,5),VAQ(17,5),
     . PDQ(17,5),DDQ(17,5),TDQ(17,5),UDQ(17,5),VDQ(17,5),
     . PR(29,19),DR(29,19),TR(29,19),UR(29,19),VR(29,19)
     . ,PQ,DQ,TQ,UQ,VQ,PQA,DQA,TQA,UA,VA,IOPQ,
     1PLP(25,10),DLP(25,10),TLP(25,10),
     2ULP(25,10),VLP(25,10),UDL(25,10),
     3VDL(25,10),UDS(25,10),VDS(25,10)
      COMMON /C4/ GLAT(16),GLON(16),NG,P4D(16,26),D4D(16,26),T4D(16,26),
     .  SP4(16,26) SD4(16,26),ST4(16,26),THET1,THET,DUMMY
      COMMON/COMPER/SPH,SDH,STH,PRH,DRH,TRH,URH,VRH,SUH,SVH,CP,
     1PRHS,DRHS,TRHS,URHS,VRHS,PRHL,DRHL,TRHL,URHL,VRHL,
     2SPHS,SDHS,STHS,SUHS,SVHS,SPHL,SDHL,STHL,SUHL,SVHL
      COMMON/WINCOM/DH,FCORY,DX5,DY5,DPX,DPY,UGH,VGH,
     $    TH,DTX,DTY,DUH,DVH,PH,UPRE,VPRE,DUPRE,DVPRE
      COMMON/CHK/PCK(4,4,3),DCK(4,4,3),NO(2)
      COMMON /CHIC/LA(4,4),NB(2),IWSYM,USH,VSH,DUSH,DVSH
      COMMON /VERT/RW1,SW1,WRH,SWH,WR(29)
```

```
C     DECLARE VARIABLES FOR BALLOON DRIFT TIMESTEP SIMULATION
      REAL LATSTEP,LONGSTEP,DELTALAT,DELTALONG,NEWLAT,NEWLONG
      INTEGER TIME,STOPDAYS,TOTDAYS,PASS
C     INITIALIZE BALLOON DRIFT TIMESTEP SIMULATION VARIABLES
      NEWLAT = 30.0
      PASS = 0
      TOTDAYS   = 0
      STOPDAYS  = 362
C     TIME STEP IS 1 HOUR: 24 TIME INCREMENTS PER DAY
      STOPDAYS = (24 * STOPDAYS)
C     FACTOR FOR RADIANS TO DEGREES                                     SCIM  43
      FAC = 57.2957795                                                  SCIM  44
      IWSYM=ICHAR(' ')                                                  SCIM  45
      IF(NPOP.NE.0) GO TO 6                                             SCIM  46
      UPRE=0.                                                           SCIM  47
      VPRE=0.                                                           SCIM  48
      DUPRE=0.                                                          SCIM  49
      DVPRE=0.                                                          SCIM  50
 6    PQ=0.                                                             SCIM  51
      DQ=0.                                                             SCIM  52
      TQ=0.                                                             SCIM  53
      PRH=0.                                                            SCIM  54
      DRH=0.                                                            SCIM  55
      TRH=0.                                                            SCIM  56
      URH=0.                                                            SCIM  57
      VRH=0.                                                            SCIM  58
      WRH = 0.                                                          SCIM  59
      UQ=0.                                                             SCIM  60
      VQ=0.                                                             SCIM  61
      PQA=0.                                                            SCIM  62
      DQA=0.                                                            SCIM  63
      TQA=0.                                                            SCIM  64
      UA=0.                                                             SCIM  65
      VA=0.                                                             SCIM  66
      PSH=0.                                                            SCIM  67
      DSH=0.                                                            SCIM  68
      TSH=0.                                                            SCIM  69
      SPU = 0.                                                          SCIM  70
      SPV = 0.                                                          SCIM  71
      MONTH=MN                                                          SCIM  72
C     PRESENT LATITUDE, DEG                                             SCIM  73
      PHI = PHIR*FAC                                                    SCIM  74
C     PRESENT LONGITUDE, DEG                                            SCIM  75
      THET = THETR*FAC                                                  SCIM  76
C     PREVIOUS LATITUDE, DEG                                            SCIM  77
      PHI1 = PHI1R*FAC                                                  SCIM  78
C     PREVIOUS LONGITUDE, DEG                                           SCIM  79
      THET1 = THET1R*FAC                                                SCIM  80
C     BEGINNING OF BALLOON DRIFT SIMULATION DO LOOP
C     DO LOOP IS FOR THE TOTAL NUMBER OF DAYS AS INITIALIZED
 196  DO 197 K = 1,STOPDAYS,1
C.....FCORY = NORTH COMPONENT CORIOLIS FACTOR TIMES DISTANCE FOR        SCIM  81
C         5 DEGREES OF LATITUDE                                         SCIM  82
      DY5 = 5000.*RI/FAC                                                SCIM  83
      DX5 = DY5*COS(PHIR)                                               SCIM  84
      FCORY = DY5*SIN(PHIR)/(120.*FAC)                                  SCIM  85
C.... IN JACCHIA OR MIXED ZONAL MEAN-JACCHIA HEIGHT RANGE               SCIM  86
    8 IF(H.GT.90.0) GO TO 10                                            SCIM  87
C.....IN 4-D DATA HEIGHT RANGE                                          SCIM  88
      IF (H.LE.25.0) GO TO 500                                          SCIM  89
C.... IN ZONAL MEAN OR MIXED ZONAL MEAN 4D HEIGHT RANGE                 SCIM  90
      GO TO 200                                                         SCIM  91
C.... IN MIXED JACCHIA-ZONAL MEAN RANGE, NEED TO FAIR DATA              SCIM  92
 10   IF (H.LT.120.) GO TO 20                                           SCIM  93
C.....FOLLOWING IS THE PURE JACCHIA HEIGHT RANGE SECTION                SCIM  94
C.....JACCHIA VALUES AT CURRENT POSITION                                SCIM  95
      CALL JACCH(H,PHIR,THET,PH,DH,TH)                                  SCIM  96
      PHIN = PHIR + 5. / FAC                                            SCIM  97
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      THETE = THET - 5.
C.....JACCHIA VALUES AT CURRENT POSITION+5 DEGREES LAT, FOR DP/DY AND
C        DT/DY
      CALL JACCH(H,PHIN,THET,PHN,DHN,THN)
C.....JACCHIA VALUES AT CURRENT POSITION-5 DEGREES LON, FOR DP/DX AND
C        DT/DX
      CALL JACCH(H,PHIR,THETE,PHE,DHE,THE)
C      DP/DY FOR GEOSTROPHIC WIND
      DPY=PHN-PH
C      DP/DX FOR GEOSTROPHIC WIND
      DPX=PHE-PH
C      DT/DX FOR THERMAL WIND SHEAR
      DTX = THE - TH
C      DT/DY FOR THERMAL WIND SHEAR
      DTY = THN - TH
C      CHANGE NOTATION FOR OUTPUT
      PGH=PH
      DGH=DH
      TGH=TH
      CALL WIND
      UH = UGH
      VH = VGH
      HB = H + 5.
      CP = 7.*PH/(2.*DH*TH)
      CALL JACCH(HB,PHIR,THET,PB,DB,TB)
      DTZ = (TB - TH)/5000.
C.....VERTICAL MEAN WIND
      WGH = -CP*(UH*DTX/DX5 + VH*DTY/DY5)/(G + CP*DTZ + UH*DUH+VH*DVH)
C      GO TO RANDOM PERTURBATIONS SECTION
      GO TO 800
C.... FOLLOWING IS THE MIXED JACCHIA-ZONAL MEAN HEIGHT RANGE SECTION
C      LOWER HEIGHT INDEX
 20   IHA = 5*(INT(H)/5)
C       UPPER HEIGHT INDEX
      IHB = IHA + 5
C     LOWER HEIGHT FOR INTERPOLATION
      HA = IHA*1.
C     UPPER HEIGHT FOR INTERPOLATION
      HB = IHB*1.
C.....JACCHIA VALUES AT LOWER HEIGHT, CURRENT LAT-LON
      CALL JACCH(HA,PHIR,THET,PJA,DJA,TJA)
      PHIN = PHIR + 5. / FAC
      THETE = THET - 5.
C.....JACCHIA VALUES AT LOWER HEIGHT, CURRENT LON-LAT+5 DEGREES
C        LAT, FOR DP/DY AND DT/DY
      CALL JACCH(HA,PHIN,THET,PJN,DJN,TJN)
C.....JACCHIA VALUES AT LOWER HEIGHT, CURRENT LAT-LON-5 DEGREES
C        LON, FOR DP/DX, AND DT/DX
      CALL JACCH(HA,PHIR,THETE,PJE,DJE,TJE)
C     JACCHIA DP/DY AT LOWER HEIGHT
      DPXJA=PJE-PJA
C      JACCHIA DP/DY AT LOWER HEIGHT
      DPYJA=PJN-PJA
C      JACCHIA DT/DX AT LOWER HEIGHT
      DTXJA = TJE - TJA
C      JACCHIA DT/DY AT LOWER HEIGHT
      DTYJA = TJN - TJA
C.....JACCHIA VALUES AT UPPER HEIGHT, CURRENT LAT-LON
      CALL JACCH(HB,PHIR,THET,PJB,DJB,TJB)
      PHIN = PHIR + 5. / FAC
      THETE=THET-5
C.....JACCHIA VALUES AT UPPER HEIGHT, CURRENT LON-LAT+5 DEGREES
C        LAT, FOR DP/DY AND DT/DY
      CALL JACCH(HB,PHIN,THET,PJN,DJN,TJN)
C.....JACCHIA VALUES AT UPPER HEIGHT, CURRENT LAT-LON-5 DEGREES
C        LON, FOR DP/DX AND DT/DX
      CALL JACCH(HB,PHIR,THETE,PJE,DJE,TJE)
C     JACCHIA DP/DX FOR GEOSTROPHIC WINDS
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      DPXJB = PJE - PJB                                                 SCIM 166
C      JACCHIA DP/DY FOR GEOSTOPHIC WINDS                               SCIM 167
      DPYJB = PJN - PJB                                                 SCIM 168
C     JACCHIA DT/DX FOR THERMAL WIND SHEAR                              SCIM 169
      DTXJB = TJE - TJB                                                 SCIM 170
C      JACCHIA DT/DY FOR THERMAL WIND SHEAR                             SCIM 171
      DTYJB = TJN - TJB                                                 SCIM 172
C.... ZONAL MEAN AT LOWER HEIGHT, TO BE FAIRED WITH JACCHIA             SCIM 173
      CALL GTERP(IHA,PHI,PGA,DGA,TGA,PG,DG,TG,DPYGA,DTYGA,UGA,UG)       SCIM 174
C.... ZONAL MEAN AT UPPER HEIGHT, TO BE FAIRED WITH JACCHIA             SCIM 175
      CALL GTERP(IHB,PHI,PGB,DGB,TGB,PG,DG,TG,DPYGB,DTYGB,UGB,UG)       SCIM 176
C.....FAIRED RESULTS AT LOWER HEIGHT                                    SCIM 177
       IHSB = 90                                                        SCIM 178
      CALL PDTUV(PSP,DSP,TSP,USP,VSP,PHI,THET,IHSB,PSH,DSH,TSH,         SCIM 179
     &  DPXSB,DPYSB, DTXSB,DTYSB,SPU,SPV)                               SCIM 180
       PGA = PGA*(1. + PSH)                                             SCIM 181
       DGA = DGA*(1. + DSH)                                             SCIM 182
       TGA = TGA*(1. + TSH)                                             SCIM 183
       PGB = PGB*(1. + PSH)                                             SCIM 184
       DGB = DGB*(1. + DSH)                                             SCIM 185
       TGB = TGB*(1. + TSH)                                             SCIM 186
      UGA=UGA+SPU                                                       SCIM 187
      VGA=SPV                                                           SCIM 188
      UGB=UGB+SPU                                                       SCIM 189
      VGB=SPV                                                           SCIM 190
       DTXGA = DTXSB * TGA                                              SCIM 191
       DTXGB = DTXSB * TGB                                              SCIM 192
       DTYGA = TGA*DTYSB + DTYGA*(1. + TSH + DTYSB)                     SCIM 193
       DTYGB = TGB*DTYSB + DTYGB*(1. + TSH + DTYSB)                     SCIM 194
       DPXGA = DPXSB * PGA                                              SCIM 195
       DPXGB = DPXSB * PGB                                              SCIM 196
       DPYGA = PGA*DPYSB + DPYGA*(1. + PSH + DPYSB)                     SCIM 197
       DPYGB = PGB*DPYSB + DPYGB*(1. + PSH + DPYSB)                     SCIM 198
       CALL FAIR(PGA,DGA,TGA,PJA,DJA,TJA,IHA,P1,D1,T1,DPXGA,DPYGA,      SCIM 199
     & DPXJA,DPYJA,DPXA,DPYA,DTXGA,DTYGA,DTXJA,DTYJA,DTXA,DTYA)         SCIM 200
C.....FAIRED RESULTS AT UPPER HEIGHT                                    SCIM 201
       CALL FAIR(PGB,DGB,TGB,PJB,DJB,TJB,IHB,P2,D2,T2,DPXGB,DPYGB,      SCIM 202
     & DPXJB,DPYJB,DPXB,DPYB,DTXGB,DTYGB,DTXJB,DTYJB,DTXB,DTYB)         SCIM 203
C.....HEIGHT INTERPOLATION ON FAIRED P,D,T                              SCIM 204
      CALL INTER2(P1,D1,T1,HA,P2,D2,T2,HB,PH,DH,TH,H)                   SCIM 205
C.....HEIGHT INTERPOLATION ON FAIRED DP/DX,DP/DY                        SCIM 206
      CALL INTERW(DPXA,DPYA,HA,DPXB,DPYB,HB,DPX,DPY,H)                  SCIM 207
C.....HEIGHT INTERPOLATION ON FAIRED DT/DX,DT/DY                        SCIM 208
      CALL INTERW(DTXA,DTYA,HA,DTXB,DTYB,HB,DTX,DTY,H)                  SCIM 209
C.... HEIGHT INTERPOLATION OF WIND                                      SCIM 210
      CALL INTERW(UGA,VGA,HA,UGB,VGB,HB,USH,VSH,H)                      SCIM 211
      DUSH=(UGB-UGA)/5000.                                              SCIM 212
      DVSH=(VGB-VGA)/5000.                                              SCIM 213
C      CHANGE OF VARIABLES FOR OUTPUT                                   SCIM 214
      PGH=PH                                                            SCIM 215
      DGH=DH                                                            SCIM 216
      TGH=TH                                                            SCIM 217
      CALL WIND                                                         SCIM 218
      UH=UGH                                                            SCIM 219
      VH=VGH                                                            SCIM 220
      CP = 7.*PH/(2.*DH*TH)                                             SCIM 221
      DTZ = (T2 - T1)/5000.                                             SCIM 222
C.....VERTICAL MEAN WIND                                                SCIM 223
      WGH = -CP*(UH*DTX/DX5 + VH*DTY/DY5)/(G + CP*DTZ + UH*DUH + VH*DVH)SCIM 224
C      GO TO RANDOM PERTURBATIONS SECTION                               SCIM 225
      GO TO 800                                                         SCIM 226
C.... THE FOLLOWING SECTION IS FOR ZONAL MEAN OR MIXED ZONAL MEAN 4D    SCIM 227
C     HEIGHTS                                                           SCIM 228
C      UPPER HEIGHT INDEX                                               SCIM 229
 200  IHGB = 5*(INT(H)/5) + 5                                           SCIM 230
C     UPPER HEIGHT                                                      SCIM 231
      HGB = IHGB*1.                                                     SCIM 232
C.... ZONAL MEAN AT UPPER HEIGHT                                        SCIM 233
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      CALL GTERP(IHGB,PHI,PGB,DGB,TGB,PG,DG,TG,DPYGB,DTYGB,UGB,UG)       SCIM 234
      IHSB = 5*(INT(H)/5) + 5                                            SCIM 235
      IF (IHSB .GT. 90)IHSB = 90                                         SCIM 236
C     UPPER STATIONARY PERTURBATION HEIGHT                               SCIM 237
 230  HSB = IHSB*1.                                                      SCIM 238
C.....STATIONARY PERTURBATIONS AT UPPER HEIGHT                           SCIM 239
      CALL PDTUV(PSP,DSP,TSP,USP,VSP,PHI,THET,IHSB,PSB,DSB,TSB,          SCIM 240
     $ DPXSB,DPYSB, DTXSB,DTYSB,USB,VSB)                                 SCIM 241
C     LOWER HEIGHT INDEX                                                 SCIM 242
      IHGA = IHGB - 5                                                    SCIM 243
C     LOWER HEIGHT INDEX                                                 SCIM 244
      HGA = IHGA*1.                                                      SCIM 245
C...  ZONAL MEAN AT LOWER HEIGHT                                         SCIM 246
      CALL GTERP(IHGA,PHI,PGA,DGA,TGA,PG,DG,TG,DPYGA,DTYGA,UGA,UG)       SCIM 247
      IHSA=IHSB - 5                                                      SCIM 248
C     LOWER STATIONARY PERTURBATION HEIGHT                               SCIM 249
 250  HSA = IHSA*1.                                                      SCIM 250
C.....STATIONARY PERTURBATIONS AT LOWER HEIGHT                           SCIM 251
      CALL PDTUV(PSP,DSP,TSP,USP,VSP,PHI,THET,IHSA,PSA,DSA,TSA,          SCIM 252
     $ DPXSA,DPYSA, DTXSA,DTYSA,USA,VSA)                                 SCIM 253
      CALL INTERW(UGA,0.,HGA,UGB,0.,HGB,UGH,VGH,H)                       SCIM 254
      CALL INTERW(USA,VSA,HSA,USB,VSB,HSB,SPU,SPV,H)                     SCIM 255
      USH=UGH+SPU                                                        SCIM 256
      VSH=SPV                                                            SCIM 257
      DUSH=((UGB-UGA)/(HGB-HGA)+(USB-USA)/(HSB-HSA))*.001                SCIM 258
      DVSH=.001*(VSB-VSA)/(HSB-HSA)                                      SCIM 259
C     FOR MIXED ZONAL MEAN - 4D SECTION                                  SCIM 260
      IF(H.LT.30.0) GO TO 300                                            SCIM 261
C.... ZONAL MEAN VALUES HEIGHT INTERPOLATIONS                            SCIM 262
      CALL INTERZ(PGA,DGA,TGA,HGA,PGB,DGB,TGB,HGB,PGH,DGH,TGH,H)         SCIM 263
C.....STATIONARY PERTURBATION HEIGHT INTERPOLATION                       SCIM 264
      CALL INTERZ(PSA,DSA,TSA,HSA,PSB,DSB,TSB,HSB,PSH,DSH,TSH,H)         SCIM 265
C     QUASI-BIENNIAL VALUES                                              SCIM 266
      CALL QBOGEN                                                        SCIM 267
C.... HEIGHT INTERPOLATION OF ZONAL MEAN DP/DY AND DT/DY                 SCIM 268
      CALL INTERW(DPYGA,DTYGA,HGA,DPYGB,DTYGB,HGB,DPYG,                  SCIM 269
     $ DTYG,H)                                                           SCIM 270
C.....HEIGHT INTERPOLATION OF STATIONARY PERTURBATION DP/DX AND DP/DY    SCIM 271
      CALL INTERW(DPXSA,DPYSA,HSA,DPXSB,DPYSB,HSB,DPXS,DPYS,H)           SCIM 272
C.....HEIGHT INTERPOLATION OF STATIONARY PERTURBATION DT/DX AND DT/DY    SCIM 273
      CALL INTERW(DTXSA,DTYSA,HSA,DTXSB,DTYSB,HSB,DTXS,DTYS,H)           SCIM 274
C.....UNPERTURBED (MONTHLY MEAN) VALUES FOR OUTPUT                       SCIM 275
      TGH = TGH * (1. + TSH)                                             SCIM 276
      PGH = PGH * (1. + PSH)                                             SCIM 277
      DGH = DGH * (1. + DSH)                                             SCIM 278
C     TOTAL DT/DX                                                        SCIM 279
      DTX =        DTXS * TGH                                            SCIM 280
C     TOTAL DT/DY                                                        SCIM 281
      DTY = TGH*DTYS + DTYG*(1. + TSH + DTYS)                            SCIM 282
C     TOTAL DP/DX                                                        SCIM 283
      DPX =        DPXS * PGH                                            SCIM 284
C     TOTAL DP/DY                                                        SCIM 285
      DPY = PGH*DPYS + DPYG*(1. + PSH + DPYS)                            SCIM 286
C.....UNPERTURBED VALUES PLUS QBO PERTURBATIONS                          SCIM 287
      PH = (1. + PQ) * PGH                                               SCIM 288
      DH = DGH * (1. + DQ)                                               SCIM 289
      TH = (1. + TQ) * TGH                                               SCIM 290
      CALL WIND                                                          SCIM 291
C     GEOSTROPHIC WIND PLUS QBO WIND PERTURBATIONS                       SCIM 292
      UH=UGH+UQ                                                          SCIM 293
      VH=VGH+VQ                                                          SCIM 294
      CP = 7.*PGH/(2.*DGH*TGH)                                           SCIM 295
      DTZ = (TGB*(1.+TSB) - TGA*(1.+TSA))/5000.                          SCIM 296
C.....VERTICAL MEAN WIND                                                 SCIM 297
C     THIS CHANGE WAS MADE 5 AUG 92 DUE TO PHONE CALL WITH MSFC JEFFRIES
C     WGH=-CP*(UGH*DTX/DX5+VGH*DTY/DY5)/(G+CP*DTZ+VGH*DUH+VGH*DVH)       SCIM 298
      WGH=-CP*(UGH*DTX/DX5+VGH*DTY/DY5)/(G+CP*DTZ+UGH*DUH+VGH*DVH)       SCIM 298
C      GO TO RANDOM PERTURBATIONS SECTION                                SCIM 299
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      GO TO 800
C.... THE FOLLOWING IS THE MIXED ZONAL MEAN-4D SECTION
C.....GENERATE GRID OF 4D PROFILES IF PREVIOUS HEIGHT GE 30
  300 IF (LOOK .EQ. 1)CALL GEN4D
      IHCK = 24
      DO 310 KND = 1,3
      IKND = IHCK + KND
      IF (IKND.GT.26)IKND=26
      DO 310 IND = 1,4
      DO 310 JND = 1,4
      PCK(IND,JND,KND) = P4D(4*(IND-1)+JND,IKND)
      DCK(IND,JND,KND) = D4D(4*(IND-1)+JND,IKND)
  310 CONTINUE
C.....LAT-LON INTERPOLATION OF 4D DATA AT 25 KM
      CALL INTER4(           PHI,THET,25,   P4D,D4D,T4D,P4A,D4A,T4A,
     $ DPX4,DPY4,DTX4,DTY4)
C.... ZONAL MEAN PLUS STATIONARY PERTURBATIONS
      PB = PGB*(1. + PSB)
C      P,D,T
      DB = DGB*(1. + DSB)
      TB = TGB*(1. + TSB)
      DPXB = PGB*DPXSB
      DPYB = PGB*DPYSB + DPYGB*(1. + PSB + DPYSB)
      DTXB = TGB*DTXSB
      DTYB = TGB*DTYSB + DTYGB*(1. + TSB + DTYSB)
C.... HEIGHT INTERPOLATION BETWEEN 4D AT 25 AND ZONAL MEAN AT UPPER
C     HEIGHT DP/DX AND DP/DY
      CALL INTERW(DPX4,DPY4,25.,DPXB,DPYB,HSB,DPX,DPY,H)
C.... HEIGHT INTERPOLATION BETWEEN 4D AT 25 AND ZONAL MEAN AT UPPER
C     HEIGHT P,D,T
      CALL INTER2(P4A,D4A,T4A,25.,PB,DB,TB,HGB,PGH,DGH,TGH,H)
C.... HEIGHT INTERPOLATION BETWEEN 4D AT 25 AND ZONAL MEAN AT UPPER
C     HEIGHT DT/DX AND DT/DY
      CALL INTERW(DTX4,DTY4,25.,DTXB,DTYB,HSB,DTX,DTY,H)
      IF (IOPQ.EQ.2) GO TO 350
C     QUASI BIENNIAL PERTURBATIONS
      CALL QBOGEN
C     ADD QBO PERTURBATIONS TO P,D,T
  350 PH=PGH*(1.+PQ)
      DH=DGH*(1.+DQ)
      TH=TGH*(1.+TQ)
      CALL WIND
C     ADD QBO WIND PERTURBATIONS
      UH=UGH+UQ
      VH=VGH+VQ
      CP = 7.*PGH/(2.*DGH*TGH)
      DTZ = (TB - T4A)/(1000.*(HGB - 25.))
C.....VERTICAL MEAN WIND
      WGH=-CP*(UGH*DTX/DX5+VGH*DTY/DY5)/(G+CP*DTZ+UGH*DUH+VGH*DVH)
C     GO TO RANDOM PERTURBATIONS SECTION
 2000 FORMAT(' 4-D DATA AFTER ADJUSTMENTS'/' LATITUDE'/3X,16F8.3)
 2001 FORMAT(' LONGITUDE'/3X,16F8.3)
 2007 FORMAT(' PRESSURE')
 2002 FORMAT(1X,I2,16F8.0)
 2003 FORMAT(' DENSITY')
 2005 FORMAT(' TEMPERATURE')
 2004  FORMAT(1X,I2,16F8.5)
 2006  FORMAT(1X,I2,16F8.2)
      GO TO 800
  500 IF (H.GE.0.0) GO TO 510
      IF (H.LT.-0.015) GO TO 505
C     IF -15 METER LE H LT 0 , H IS SET TO 0
      H = 0.
      GO TO 510
C     NO MORE COMPUTATIONS TO BE MADE IF HEIGHT LT -5 M
  505 NMORE = 0
       RETURN
C.....GENERATE GRID OF 4D PROFILES IF PREVIOUS HEIGHT GE 30
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 510  IF (LOOK .EQ. 1)CALL GEN4D
C      LOWER HEIGHT INDEX
       IHA=INT(H)
C      LOWER HEIGHT INDEX
       HA = IHA*1.
      IWSX = IWSYM
      IHCK=IHA-1
      DO 511 KND=1,3
      IKND = IHCK + KND
      IF (IKND.LT.1)IKND = 1
      IF (IKND.GT.26)IKND = 26
      DO 511 IND=1,4
      DO 511 JND = 1,4
      PCK(IND,JND,KND)=P4D(4*(IND-1)+JND,IKND)
      DCK(IND,JND,KND)=D4D(4*(IND-1)+JND,IKND)
511   CONTINUE
C      UPPER HEIGHT INDEX
       IHB = IHA + 1
       IF(IHB.LE.25) GO TO 513
       IHA=24
       HA=24.
       IHB=25
C       UPPER HEIGHT
  513 HB = IHB*1.
C.....LAT-LON INTERPOLATION OF 4D VALUES AT UPPER HEIGHT
  515 CALL INTER4(          PHI,THET,IHB,   P4D,D4D,T4D,PB,DB,TB,
     $ DPX4B,DPY4B,DTX4B,DTY4B)
      IF(IHA.EQ.0.AND.PB*DB*TB.LE.0.)GO TO 520
      GO TO 540
  520 IHB=IHB+1
C.....LOOP TO FIND LOWEST VALID HEIGHT
      HB=HB+1.
      GO TO 515
  540 IF(IHA.GT.0)CALL INTER4(          PHI,THET,IHA,   P4D,D4D,T4D,
     $ PA,DA,TA,DPX4A,DPY4A,DTX4A,DTY4A)
      IF(IWSYM.EQ.ICHAR('*')) IWSX=IWSYM
      IF(IHA.EQ.0.OR.(PA*DA*TA.LE.0.AND.IHA.LT.10.AND.PB*DB*TB.GT.0.))
     1GO TO 550
      GO TO 600
C.....LAT-LON INTERPOLATION OF 4D VALUES AT LOWER HEIGHT
  550 CALL INTER4(          PHI,THET,0,    P4D,D4D,T4D,
     $ PA,DA,TA,DPX4A,DPY4A,DTX4A,DTY4A)
      IF(IWSYM.EQ.ICHAR('*')) IWSX=IWSYM
      IF(TA-TB)560,570,560
  560  IF(TA*TB.LE.0.0) GO TO 570
       TZ = (TA-TB) / ALOG(TA/TB)
      GO TO 575
  570 TZ=TA
C ...COMPUTES HEIGHT OF SURFACE
 575   HA = HB
       IF(PB*PA.LE.0.0)GO TO 576
       HA = HB + 0.28705*TZ*ALOG(PB/PA)/G
 576   IF(H.GT.HA - 0.04)GO TO 600
      PH=0.
      DH=0.
      TH=0.
      PGH=0.
      DGH=0.
      TGH=0.
      GO TO 800
C.....HEIGHT INTERPOLATION OF P,D,T
  600 CALL INTER2(PA,DA,TA,HA,PB,DB,TB,HB,PGH,DGH,TGH,H)
C.....HEIGHT INTERPOLATION OF DP/DX AND DP/DY
      CALL INTERW(DPX4A,DPY4A,HA,DPX4B,DPY4B,HB,DPX,DPY,H)
C.....HEIGHT INTERPOLATION OF DT/DX AND DT/DY
      CALL INTERW(DTX4A,DTY4A,HA,DTX4B,DTY4B,HB,DTX,DTY,H)
C      CHANGE OF NOTATION FOR OUTPUT
      PH = PGH
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      DH = DGH
      TH = TGH
      IF(PH*DH*TH.LE.0.) GO TO 800
      CALL WIND
C      CHANGE OF NOTATION FOR OUTPUT
      UH = UGH
      VH = VGH
      CP = 7.*PGH/(2.*DGH*TGH)
      DTZ = (TB - TA)/(1000.*(HB - HA))
C.... VERTICAL MEAN WIND
      WGH = -CP*(UGH*DTX/DX5 + VGH*DTY/DY5)/(G+CP*DTZ+UH*DUH+VH*DVH)
C     QBO=0 IF H LT 10
      IF (H.LT.10.) GO TO 800
      IF (IOPQ.EQ.2) GO TO 650
C     COMPUTES QUASI BIENNIAL PERTURBATIONS
      CALL QBOGEN
C     ADDS QBO PERTURBATIONS TO P,D,T
  650 PH=PGH*(1.+PQ)
      DH=DGH*(1.+DQ)
      TH=TGH*(1.+TQ)
C     ADDS QBO WIND PERTURBATIONS TO U,V
      UH=UGH+UQ
      VH=VGH+VQ
C.....THE FOLLOWING IS THE RANDOM PERTURBATIONS SECTION
C.....NO RANDOM PERTURBATIONS IF IOPR GT 1
  800 CONTINUE
      IF(H .GE. 30.)GOTO 512
      IF(IPRT.NE.0)GOTO 512
      WRITE(6,2000) (GLAT(I),I=1,NG)
      WRITE(6,2001) (GLON(I),I=1,NG)
      WRITE(6,2007)
      DO 504 I=1,26
      IH=I-1
       WRITE(6,2004)IH,(SP4(J,I),J=1,NG)
      WRITE(6,2002) IH,(P4D(J,I),J=1,NG)
  504 CONTINUE
       WRITE(6,2003)
       DO 507 I = 1,26
       IH = I - 1
       WRITE(6,2004)IH,(SD4(J,I),J=1,NG)
 507   WRITE(6,2004)IH,(D4D(J,I),J=1,NG)
       WRITE(6,2005)
       DO 506 I = 1,26
       IH = I - 1
       WRITE(6,2004)IH,(ST4(J,I),J=1,NG)
 506   WRITE(6,2006)IH,(T4D(J,I),J=1,NG)
      IPRT=IPRT+1
  512 CONTINUE
       IF(NPOP.EQ.0)GO TO 840
      IF (IOPR.GT.1) GO TO 830
C.....INTERPOLATES RANDOM WIND MAGNITUDES TO HEIGHT H, LATITUDE PHI
      CALL INTRUV(UR,VR,H,PHI,SUH,SVH)
      CALL INTR25(PLP,DLP,H,PHI,PLPH,DLPH)
      CALL INTR25(TLP,DLP,H,PHI,TLPH,DLPH)
      CALL INTR25(ULP,VLP,H,PHI,ULPH,VLPH)
      CALL INTR25(UDL,VDL,H,PHI,UDL2,VDL2)
      CALL INTR25(UDS,VDS,H,PHI,UDS2,VDS2)
      CALL INTRW(WR,H,SWH)
      SUHL=SQRT(ULPH*ABS(SUH))
      SUHS=SQRT((1.-ULPH)*ABS(SUH))
      SVHL=SQRT(VLPH*ABS(SVH))
      SVHS=SQRT((1.-VLPH)*ABS(SVH))
      SUH = SQRT(ABS(SUH))
      SVH = SQRT(ABS(SVH))
       IF(H.GE.25.)GOTO 805
C..... IF H LE 20 USE 4D DATA RANDOM P,D,T SIGMAS
       IF(H.LE.20.)GOTO 810
C.....INTERPOLATE PR,DR,TR ARRAYS TO GET P,D,T SIGMAS AT HEIGHT H,
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C        LATITUDE PHI
       CALL RTERP(25.,PHI,PR,DR,TR,SPHG,SDHG,STHG)
       GO TO 810
 805   CONTINUE
      CALL RTERP(H,PHI,PR,DR,TR,SPH,SDH,STH)
      GO TO 820
C.....LAT-LON INTERPOLATION ON P,D,T SIGMAS AT LOWER HEIGHT
  810 CALL INTER4(          PHI,THET,IHA,   SP4,SD4,ST4,PA,DA,TA,
     $ DPX,DPY,DTX,DTY)
C..... LAT-LON INTERPOLATION ON P,D,T SIGMAS AT UPPER HEIGHT
      CALL INTER4(          PHI,THET,IHB,   SP4,SD4,ST4,PB,DB,TB,
     $ DPX,DPY,DTX,DTY)
C.....HEIGHT INTERPOLATION OF SIGMAS
      CALL INTERZ(PA,DA,TA,   HA,PB,DB,TB,   HB,SPH,SDH,STH,H)
       IF(PH.LE.0.0.OR.DH.LE.0.0.OR.TH.LE.0.0)GO TO 825
       IF(H.LE.20.)GOTO 820
       FH = 1. - 0.2*(25. - H)
       SPH = FH*SPHG + (1. - FH)*SPH
       SDH = FH*SDHG + (1. - FH)*SDH
       STH = FH*STHG + (1. - FH)*STH
C.....HEIGHT DISPLACEMENT BETWEEN PREVIOUS AND CURRENT POSITION
  820 DZ = H1 - H
      SPHL=SQRT(PLPH*ABS(SPH))
      SPHS=SQRT((1.-PLPH)*ABS(SPH))
      SDHL=SQRT(DLPH*ABS(SDH))
      SDHS=SQRT((1.-DLPH)*ABS(SDH))
      STHL=SQRT(TLPH*ABS(STH))
      STHS=SQRT((1.-TLPH)*ABS(STH))
      SPH = SQRT(ABS(SPH))
      SDH = SQRT(ABS(SDH))
      STH = SQRT(ABS(STH))
C.....COMPUTES HORIZONTAL DISPLACEMENT DX BETWEEN PREVIOUS AND CURRENT
C        POSITION, HORIZONTAL SCALE HL, AND VERTICAL SCALE VL
C.... COMPUTES PERTURBATION VALUES PRH,DRH,TRH,URH,VRH AND WRH
      CALL PERTRB
C     ADDS RANDOM PERTURBATIONS TO PH,DH,TH
      PH = PH*(1. + PRH)
      DH = DH*(1. + DRH)
      TH = TH*(1. + TRH)
C     ADDS RANDOM WINDS TO UH,VH,WH
      UH=UH+URH
      VH=VH+VRH
      WH=WGH+WRH
C.....SETS PREVIOUS RANDOM PERTURBATION IN P,D,T TO CURRENT
C        PERTURBATIONS, FOR NEXT CYCLE
  825 RP1S= PRHS
      RD1S= DRHS
      RT1S= TRHS
      RP1L=PRHL
      RD1L=DRHL
      RT1L=TRHL
C.... SETS PREVIOUS MAGNITUDES TO CURRENT VALUES, FOR NEXT CYCLE
      SP1S=SPHS
      SD1S= SDHS
      ST1S=STHS
      SP1L=SPHL
      SD1L=SDHL
      ST1L=STHL
C.....SETS PREVIOUS WIND PERTURBATION VALUES TO CURRENT VALUES,
C        FOR NEXT CYCLE
      RU1S=URHS
      RV1S=VRHS
      RU1L=URHL
      RV1L=VRHL
      RW1=WRH
C.....SETS PREVIOUS WIND PERTURBATION MAGNITUDES TO CURRENT VALUES,
C        FOR NEXT CYCLE
      SU1S=SUHS
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      SV1S=SVHS
      SU1L=SUHL
      SV1L=SVHL
      SW1=SWH
C.....SETS PREVIOUS HEIGHT TO CURRENT HEIGHT, FOR NEXT CYCLE
  830 H1 = H
C.....SETS PREVIOUS LATITUDE TO CURRENT LATITUDE, FOR NEXT CYCLE
      PHI1R=PHIR
C.....SETS PREVIOUS LONGITUDE TO CURRENT LONGITUDE, FOR NEXT CYCLE
      THET1R=THETR
C     SETS NMORE TO COMPUTE MORE DATA ON NEXT CYCLE
  840   NMORE = 1
C.....NO MORE DATA IF P, D, OR T LEQ 0
      IF(PH*DH*TH.LE.0.) RETURN
      CALL STDATM(H,TS,PS,DS)
      IF ((PS*DS*TS).GT.0.) GO TO 870
      PGHP=0.
      DGHP=0.
      TGHP=0.
      PHP=0.
      DHP=0.
      THP=0.
      GO TO 880
  870 PGHP=100.*(PGH-PS)/PS
      DGHP=100.*(DGH-DS)/DS
      TGHP=100.*(TGH-TS)/TS
      PHP=100.*(PH-PS)/PS
      DHP=100.*(DH-DS)/DS
      THP=100.*(TH-TS)/TS
C     CONVERTS QBO P,D,T TO PERCENT
  880 PQ=100.*PQ
      DQ=100.*DQ
      TQ=100.*TQ
C     CONVERTS RANDOM P,D,T TO PERCENT
      PRH=100.*PRH
      DRH=100.*DRH
      TRH=100.*TRH
      PRHS=100.*PRHS
      DRHS=100.*DRHS
      TRHS=100.*TRHS
      PRHL=100.*PRHL
      DRHL=100.*DRHL
      TRHL=100.*TRHL
      SPHS = 100.*SPHS
      SDHS = 100.*SDHS
      STHS = 100.*STHS
      SPHL = 100.*SPHL
      SDHL = 100.*SDHL
      STHL = 100.*STHL
C     CONVERTS WIND SHEAR TO M/S/KM
      DUH = DUH * 1000.
      DVH = DVH * 1000.
      PQA=PQA*100.
      DQA=DQA*100.
      TQA=TQA*100.
      SPH=SPH*100.
      SDH=SDH*100.
      STH=STH*100.
      PSH=PSH*100.
      DSH=DSH*100.
      TSH=TSH*100.
      IF(NPOP.NE.0) GO TO 920
      UPRE=UGH
      VPRE=VGH
      DUPRE=DUH/1000.
      DVPRE=DVH/1000.
      RETURN
 920  IF (IOPP.NE.0)
```

```
      * WRITE(IOPP,951)H,PHI,THET,DGHP,TGH,UGH,VGH,WGH,SDHL,STHL,       SCIM 640
      & SUHL,SVHL                                                       SCIM 641
 951    FORMAT(F5.1,7F7.2,4F6.2)                                        SCIM 642
C        WRITE(6,900) H,PHI,THET,PGH,DGH,TGH,UGH,CHAR(IWSYM),           SCIM 643
C      1 VGH,PH,DH,TH,UH,CHAR(IWSYM),VH,DUH,                            SCIM 644
C      $ DVH,SWH,IET,PGHP,DGHP,TGHP,WGH,PHP,DHP,THP,WH,PSH,DSH,TSH,     SCIM 645
C      $ SPU,SPV,PQ,DQ,TQ,UQ,                                           SCIM 646
C      $ VQ,PQA,DQA,TQA,UA,VA,PRHS,DRHS,TRHS,URHS,VRHS,SPHS,SDHS,STHS,  SCIM 647
C      1SUHS,SVHS,PRHL,DRHL,TRHL,URHL,VRHL,SPHL,SDHL,STHL,SUHL,SVHL,    SCIM 648
C      2PRH,DRH,TRH,URH,VRH,SPH,SDH,STH,SUH,SVH                         SCIM 649
C900    FORMAT(1X,F6.2,2F7.2,2(2E9.3,2F6.0,A1,F5.0),2F5.1,23X,F6.2/1X,  SCIM 650
C      1 I5,14X,2(F8.1,' '),F6.1,' ',E10.2,1X,                          SCIM 651
C      & 2(F8.1,' '),F6.1,' ',F10.2,11X,                                SCIM 652
C      23F5.1,2F5.0,' SP'/102X,3F5.1,2F5.0,' OBO'/102X,3F5.1,2F5.0,' MAG'/SCIM 653
C      3 102X,3F5.1,2F5.0,' RANS'/102X,3F5.1,2F5.0,' SIGS'/             SCIM 654
C      4102X,3F5.1,2F5.0,' RANL',/                                      SCIM 655
C      5102X,3F5.1,2F5.0,' SIGL',/                                      SCIM 656
C      6102X,3F5.1,2F5.0,' RANT',/                                      SCIM 657
C      7102X,3F5.1,2F5.0,' SIGT',/)                                     SCIM 658
C        NEXT THREE LINES PRINT OUT LAT,LONG, E-W WIND, N-S WIND
C         PRINT*,'LAT, LONG, E-W WIND, N-S WIND'
C         WRITE(6,9091) PHI,THET,UH,CHAR(IWSYM),VH
C9091    FORMAT(1X,2(F7.2,6X),F6.0,A1,F5.0,/)
C        MULTIPLY WIND SPEED AND WIND DIRECTION BY TIME STEP TO
C        CREATE WIND VECTORS FOR THE TIME STEP IN KILOMETERS
C        GIVEN A TIME STEP OF 1 HOUR WITH 60 SEC/MIN, 60 MIN/HR
         LONGSTEP  = UH * 60 * 60 * 1 / 1000
         LATSTEP   = VH * 60 * 60 * 1 / 1000
         DELTALAT  = LATSTEP / 111
         DELTALONG = LONGSTEP / ((COS(PHI/FAC)) * 111.4)
         DELTALONG = MOD(DELTALONG,360.0)
C        APPLY WIND VECTORS TO LAT/LONG (COMPUTE NEW LAT/LONG)
         IF (ABS(NEWLAT).EQ. 90) THEN
           NEWLAT = PHI - DELTALAT
         ELSE
           NEWLAT  = PHI + DELTALAT
         ENDIF
         IF (NEWLAT .GT. 90) THEN
           NEWLAT = 90-(NEWLAT - 90)
         ELSE
           CONTINUE
         ENDIF
         IF (NEWLAT .LT. -90) THEN
           NEWLAT = ABS(NEWLAT) - 180
         ELSE
           CONTINUE
         ENDIF
         PHI1R   = PHI * FAC
         PHIR    = NEWLAT * FAC
         PHI     = NEWLAT
         NEWLONG = THET - DELTALONG
         IF (NEWLONG .GT. 180) THEN
           NEWLONG = NEWLONG - 360
         ELSE
           CONTINUE
         ENDIF
         IF (NEWLONG .LT. -180) THEN
           NEWLONG = NEWLONG + 360
         ELSE
           CONTINUE
         ENDIF
         THET1R  = THET * FAC
         THETR   = NEWLONG * FAC
         THET    = NEWLONG
C         WRITE(6,9092) LATSTEP,LONGSTEP,DELTALAT,DELTALONG,
C        $NEWLAT,NEWLONG
C9092     FORMAT(1X,'LATSTEP(KM) LONGSTEP(KM)',1X,
C        $'DELTALAT(DEG) DELTALONG(DEG) NEWLAT(DEG) NEWLONG(DEG)',/,
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C      $1X,F5.0,8X,F6.0,7X,F5.0,9X,F6.0,12X,F5.0,7X,F6.0,/)
C      CHECK LONGITUDE PICKET; RECORD LATITUDE IF LONGITUDE IS MET
C      CURRENT WRITE STATEMENT WRITES LATITUDE TO A FILE
       IF (NEWLONG.LT.-42.0 .AND. NEWLONG.GT.-46.0 .AND. PASS.EQ.0) THEN
         PASS = 1
C        WRITE(9,9093) NEWLAT
C9093    FORMAT(1X,F6.2)
       ELSE
         CONTINUE
       ENDIF
C        INCREMENT TIME AND CHECK STOPPING RULE
         TIME = TIME + 1
         IF (TIME .GT. 23) THEN
           DAYCOUNT = DAYCOUNT + 1
C          PRINT*,'INSIDE TIME LOOP'
           TIME = 0
C         WRITE(6,9094) LATSTEP,LONGSTEP,DELTALAT,DELTALONG,
C      $NEWLAT,NEWLONG
C9094   FORMAT(1X,'LATSTEP(KM) LONGSTEP(KM)',1X,
C      $'DELTALAT(DEG) DELTALONG(DEG) NEWLAT(DEG) NEWLONG(DEG)',/,
C      $1X,F5.0,8X,F6.0,7X,F5.0,9X,F6.0,12X,F5.0,7X,F6.0,/)
           IF (DAYCOUNT .GT. 30) THEN
C            PRINT*,'INSIDE DAYCOUNT LOOP'
             MN = MN + 1
             MONTH = MN
C            PRINT*,'MONTH IS CHANGED'
             DAYCOUNT = 0
             IF (MONTH .GT. 12) THEN
               IYR = IYR + 1
               MN = 1
               MONTH = MN
C               WRITE(6,9095) IYR
C 9095          FORMAT(1X,I2,/)
             ELSE
               CONTINUE
             ENDIF
C             WRITE(6,9099) MONTH
C 9099        FORMAT(1X,I3,/)
           ELSE
             CONTINUE
           ENDIF
         ELSE
           CONTINUE
         ENDIF
C        LOCATION AFTER 10 DAYS OF 24 HOURS PER DAY TIME INCREMENTS
         IF (TOTDAYS .EQ. 240) THEN
           WRITE(7,9096) NEWLAT,NEWLONG
 9096      FORMAT(1X,F6.2,2X,F7.2)
         ELSE
           CONTINUE
         ENDIF
C        LOCATION AFTER 30 DAYS OF 24 TIME INCREMENTS PER DAY
         IF (TOTDAYS .EQ. 720) THEN
           WRITE(9,9097) NEWLAT,NEWLONG
 9097      FORMAT(1X,F6.2,2X,F7.2)
         ELSE
           CONTINUE
         ENDIF
C        LOCATION AFTER 360 DAYS OF 24 TIME INCREMENTS PER DAY
         IF (TOTDAYS .EQ. 8640) THEN
           WRITE(8,9098) NEWLAT,NEWLONG
 9098      FORMAT(1X,F6.2,2X,F7.2)
         ELSE
           CONTINUE
         ENDIF
         TOTDAYS = TOTDAYS + 1
C      IF (NEWLONG .LT. -46.0 .AND. NEWLONG .GT. -50.0) THEN
C        PASS = 0
```

```
C     ELSEIF (NEWLONG .LT. -38.0 .AND. NEWLONG .GT. -42.0) THEN
C       PASS = 0
C     ELSE
C       CONTINUE
C     ENDIF
  197 CONTINUE
C 197 PRINT*,'END OF DO LOOP'
      RETURN                                                            SCIM 659
      END                                                               SCIM 660
```

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